IN-SITU MAINTENANCE-FREE MEASUREMENT OF SOILING-INDUCED POWER LOSSES IN PV ARRAYS

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ABSTRACT: The accumulation of dust, dirt, and other contaminants, referred to as soiling, is a major contributor to energy loss in photovoltaic (PV) systems, particularly in desert environments. Soiling is primarily quantified by the soiling ratio, representing the ratio of actual PV power output to that expected under clean conditions. Although different types of soiling sensors are available, accurate soiling measurements often require comparing the maximum power output of soiled PV modules to the expected output for clean modules, particularly when soiling accumulates non-uniformly on module surfaces. In-situ module-level I-V measurement units now provide a direct means to measure the maximum power output of soiled modules within a PV array, eliminating the necessity for standalone reference modules. However, determining the anticipated power output in a clean state for modules typically involves a comparison with regularly cleaned reference modules, posing challenges for operations and maintenance. In this study, we assess an instrumentation system designed to measure actual power losses due to soiling without relying on the periodic cleaning of reference devices. In-situ I-V measurements determine the actual power output, while soiling-compensated irradiance measurements are used to determine the expected clean-state power without the need for regular maintenance. Testing is ongoing in the desert environment of Qatar. Results from the first four months of testing reveal good performance in soiling measurement compared to a control system comprising a soiled module and a regularly cleaned module whose power outputs are directly compared.
Keywords: soiling, bifacial PV, rear irradiance, maintenance

1 INTRODUCTION

Soiling, the accumulation of dust, dirt, and other contaminants, is one of the principal reasons for energy loss in PV systems [1][2] and therefore must be quantified accurately to assess system performance. Soiling measurement is used for various purposes, including pre-construction resource assessment, identifying losses during commissioning and capacity tests, assessing performance against guarantees, and of course, optimizing cleaning schedules for operations and maintenance (O&M).

Soiling is quantified by the soiling ratio (SR), the ratio of actual PV power output to expected output under clean conditions [3]. Numerous types of soiling sensors have been developed to measure soiling ratio. However, many of these sensors only provide an approximation of the true soiling ratio, for example by measuring the short-circuit current (I_{sc}) of reference devices as a proxy for module power or by utilizing small-area devices such as reference cells or optical dust sensors. The most accurate measurements of soiling losses require comparing the maximum power (P_{max}) of measured soiled PV modules to the expected maximum power output for a clean module.



Figure 1: Outdoor Test Facility (OTF) of the Qatar Environment and Energy Institute (QEERI), showing extensive soiling.



Figure 2: No-maintenance soiling measurement instrumentation at QEERI's OTF. Left: in-situ I-V unit (RDE300i) mounted beneath module racking, which measures periodic I-V sweeps on one of the modules without disconnection from the array. Center: rear-side reference cells (RC22), which are designed to mount compactly within the module frame area in multiple positions without shading the rear side of the PV cells. Right: front-side RC22 reference cell coupled with Mars™ optical soiling sensor, to provide soiling-compensated irradiance values without cell cleaning.

This is especially true when soiling accumulation is non-uniform across the modules, with concentrated bands of soiling at module edges [4][5][6][7], which causes a divergence between true soiling ratio and approximate measurements from many typical sensors.

In-situ module-level I-V measurement units [7] now enable the direct measurement of the maximum power output of soiled PV modules, the numerator of *SR*, while they are still connected to a PV array, eliminating the need for standalone reference modules.

How is the expected power, the denominator of *SR*, to be determined? A simple approach to *SR* measurement is to compare the P_{max} of a soiled module to that of a regularly cleaned module. In this approach ("module-module") the clean module power output provides the expected power for the denominator of *SR*. However, this requires regularly cleaning the clean reference module, which may impose a burden on busy operations and maintenance (O&M) personnel.

Here we evaluate a new instrumentation approach that allows measuring actual power losses due to soiling to measure true *SR*, but without the need for any cleaning operations by O&M. The approach uses in-situ I-V measurements to determine the power output of a soiled module within a PV array while incorporating measurements of soiling-compensated irradiance, achieved by coupling a PV reference cell with an optical soiling sensor, to determine the expected clean-state power of the soiled module. In this appraoch ("module-cell-optical") measurements are performed without requiring regular maintenance for cleaning reference devices.

2 EXPERIMENT

Our study is being conducted in the harsh and dusty desert environment at the Outdoor Test Facility (OTF) of the Qatar Environment and Energy Research Institute (QEERI), shown in Figure 1. The soiling rate at this location is very high, typically ~0.3-0.5% per day [2][8], making it an excellent location for testing soiling measurement.

Equipment for evaluating the module-cell-optical soiling measurement approach was installed in early 2024. The system is installed on a string with 440 W bifacial crystalline silicon modules and is comprised of several instruments, shown in Figure 2. An in-situ I-V measurement unit (RDE300i) periodically measures I-V curves of its associated PV module and determines the module's P_{max} while the module contributes to normal power production in between I-V sweeps. Two rear-side reference cells (RC22) are installed to the east and west sides of the measured module to measure rear-side irradiance contributions. An additional reference cell (RC22) is installed on the front-side of the array together with an optical soiling sensor (Mars™) used for correcting the front-side irradiance reading, eliminating the need for sensor cleaning. The Mars sensor has been previously validated at this site and found to measure soiling rates in agreement with other methods [2][9].

Soiling ratio measurements from the system under evaluation are compared to a control system which comprises a pair of soiled/clean reference modules which are continuouslly held at Pmax by an max-power-point tracking electronic load system. The clean module in this pair is cleaned weekly.

The test string and the control system are normally completely cleaned every two month providing a periodic reset to the experiments.

Tests began in early 2024 and are ongoing, expected to continue through mid 2025.

3 EQUATIONS

We calculate soiling ratio *SR* as the ratio of the measured power of the soiled module to its expected power when clean, using the formula

$$SR = \frac{P_{\mathrm{max}}^{\mathrm{soiled}}}{P_{\mathrm{max},0}^{\mathrm{soiled}} \cdot \left(1+\gamma \cdot \left(T^{\mathrm{soiled}} - T_0\right)\right) \cdot \left(G_{\mathrm{tot}}/G_0\right)} \quad (1)$$

where $P_{\mathrm{max}}^{\mathrm{soiled}}$ is the maximum power of the soiled module determined from its I-V curve, $P_{\mathrm{max},0}^{\mathrm{soiled}}$ is the maximum power of the soiled module when it is completely clean and at reference conditions of irradiance and temperature, γ is the module's maximum power temperature coefficient, T^{soiled} is the module's measured temperature, T_0 is the reference condition temperature (e.g. 25 °C), G_{tot} is the total effective front plus rear POA irradiance, and G_0 is the reference condition irradiance (e.g. 1000 W/m^2). We

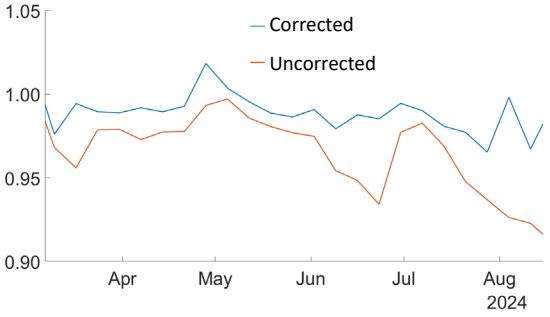


Figure 3: Normalized ratio of uncorrected (soiled) and corrected (soiling-compensated) front-side RC22 reference cell irradiance readings to readings from a regularly-cleaned reference cell.

use the two rear-side and one front-side reference cells to estimate the average total effective irradiance illuminating the soiled module from front and rear, according to the formula

$$G_{\mathrm{tot}} = G_{\mathrm{front}} + \varphi \cdot \left(G_{\mathrm{rear,E}} + G_{\mathrm{rear,W}}\right)/2 \qquad (2)$$

where G_{front} is the irradiance measured by the front reference cell after correction for soiling losses by the reading of the Mars sensor, $G_{\mathrm{rear,E}}$ and $G_{\mathrm{rear,W}}$ are the irradiances measured by the rear east and west cells, and φ is the PV module bifaciality factor. Averaging the two rear-side cells allows for estimating the average irradiance across the module's rear plane. The bifaciality factor φ appears in eq. (2) to account for the lower responsivity of the module to rear-side light relative to front side light.

The front-side irradiance G_{front} is calculated by

$$G_{\mathrm{front}} = G_{\mathrm{front}}^{\mathrm{uncorr}} \cdot (1 + SL) \qquad (3)$$

where $G_{\mathrm{front}}^{\mathrm{uncorr}}$ is the uncorrected irradiance read from the non-cleaned front-side RC22 reference cell and SL is the fractional soiling loss recorded by the Mars soiling sensor to which the front-side RC22 is mounted (see Fig. 2).

4 RESULTS

The main principle behind the approach evaluated here is that the non-cleaned front-side RC22 reference cell can be compensated for soiling losses using the Mars optical soiling sensor. Fig. 3 presents a validation of this principle. The plot shows the normalized ratio of the weekly average uncorrected (soiled) and corrected (soiling-compensated, using eq. (3)) front-side RC22 irradiance to a irradiance readings from a separate regularly cleaned front-side reference cell. The ratio of the uncorrected readings declines as soiling builds up on the RC22 and the Mars sensor, reaching losses of approximately 6% and 8% in late June and late August, respectively, and increases when the system is cleaned, for example at the beginning of July, while the ratio of the corrected readings stays near 1.0, demonstrating the soiling compensation.

Fig. 4 shows soiling ratios measured by multiple methods during the study to date. The black line shows soiling ratio measured by the Mars soiling sensor. The pink trace shows the P_{max}-based soiling ratio of the PV module in the test system determined using the module-cell-optical combination of the RDE300i, Mars, and RC22 devices, calculated using eq. (1), (2), and (3). The blue trace shows a similar I_{sc}-based soiling ratio, calculated using a modified form of eq. (1) in which $P_{\mathrm{max}}^{\mathrm{soiled}}$ is replaced by $I_{\mathrm{sc}}^{\mathrm{soiled}}$, the I_{sc} of the soiled module measured by the RDE300i, and $P_{\mathrm{max,0}}^{\mathrm{soiled}}$ is replaced by $I_{\mathrm{sc,0}}^{\mathrm{soiled}}$, the clean-state value of I_{sc} at reference conditions. The dashed brown trace shows soiling ratio of the control system, calculated by the ratio of P_{max} between the soiled and clean modules in the control module pair.

At the beginning of May, July, and September the test string with the module-cell-optical system (RDE300i, Mars, and RC22 devices) was cleaned to reset the experiment, while the Control system was cleaned at the beginning of May and September only.

Fig. 4 shows that the soiling ratios measured by the module-cell-optical system are similar to those measured by the control system in the two-month period May to July, with soiling reaching approximately 6% loss at the end of June. The data also appear to show a lower soiling ratio for the P_{max}-based SR than for the I_{sc}-based SR, which is typical of conditions where soiling accumulates non-uniformly. Fig. 5 shows a photograph of soiling on the test

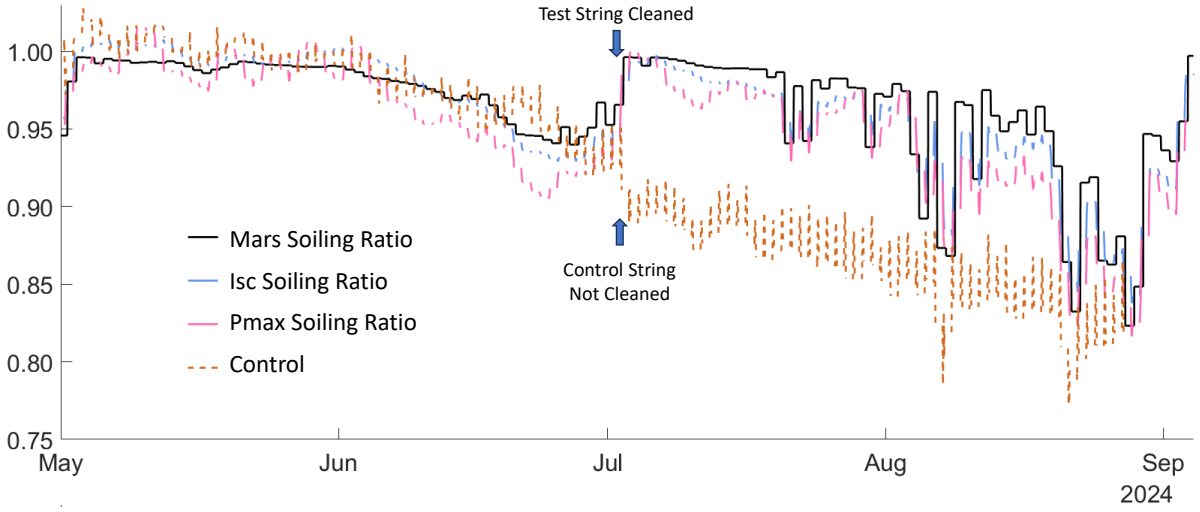


Figure 4: Soiling ratios calculated using multiple methods over a 4-month period.

module taken at the end of June, prior to cleaning, which indeed appears to show soiling accumulation near the bottom edge of the module, consistent with the lower Pmax soiling ratio. The ability to measure this phenomenon is the benefit of using I-V data in soiling measurements.

During July and August the module-cell-optical test system results cannot be directly compared to the Control system, which was not cleaned in July. However, qualitatively, the data in Fig. 4 show both systems measuring approximately 6% increase in soiling loss between the beginning of July and end of August.

The rear-side reference cells remained clean during the study period, as verified by visual observation.

Several technical points of the data are under review. We wish to evaluate how well the rear-side irradiance sensors capture the average rear-side irradiance contribution sensed by the soiled PV module. A previous study on a single-axis tracking system [10] demonstrated good agreement between the average rear-side reference cell irradiance and the module performance; however, the current test system is fixed tilt and may therefore behave differently. Collecting data for a longer period will help us evaluate these points by observing any seasonal variations.

Note that while the study was performed without cleaning the front-side Mars/RC22 combination, except during the bi-monthly experiment resets, the measurement approach would still be valid if the Mars/RC22 combination were occasionally cleaned. The approach eliminates the requirement of regular cleaning – easing the burden on O&M staff – while still allowing for irregular cleaning if desired to improve measurement accuracy.

CONCLUSIONS

Our ongoing study evaluates an approach to maintenance-free measurement of power losses due to soiling in a PV array using a combination of in-situ I-V measurements, front and rear reference cells, and an optical soiling sensor. The combination of instruments allows measuring true soiling ratio, including the effect of non-uniform soiling on module power losses, without requiring periodic cleaning of reference devices. Results from the first four months of testing validate the approach. Additional data will be collected at this site through mid-2025.

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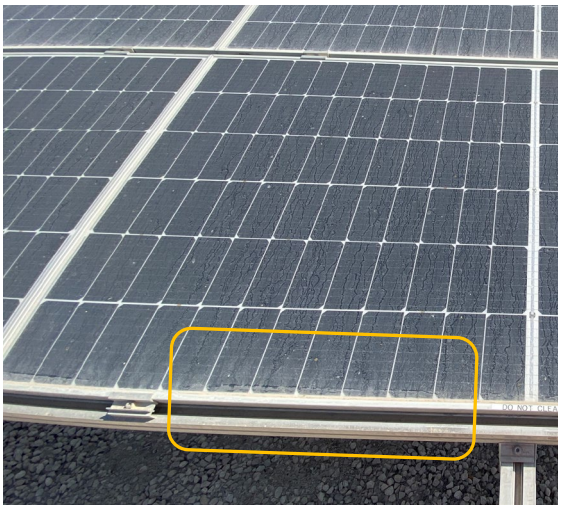


Figure 5: Soiled module at the end of June, showing non-uniform soiling accumulation near the module edge.