Working towards the development of a standardized artificial soiling method

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Working towards the Development of a Standardized Artificial Soiling Method
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Abstract — Solar glass coatings for photovoltaic (PV) modules include antireflection and antisoiling coatings. There are increasing number of claims related to dust resistant, abrasion resistant (during cleaning) and self-cleaning solar glass coatings. Currently, there is no standardized way of verifying the validity of such claims. As a first step towards validating such claims, the industry needs to develop a standardized artificial soiling method with actual laminated module construction of glass / EVA / cell / EVA / backsheet. This paper presents an approach for working towards the development of a standardized artificial soiling method for laminated photovoltaic (PV) cells or mini-modules. In this study, poly-Si mini-modules and single-cell mono-Si coupons were soiled and characterized using I-V, reflectance and quantum efficiency (QE) to calculate the effect of soiling on performance.

Index Terms — Performance loss, Photovoltaic Cells, Soiling.

I. INTRODUCTION

The effect of soil on performance of photovoltaic (PV) modules can be significant for a site depending on a wide variety of reasons ranging from environmental conditions to system orientation and tilt [1]. The average annual soiling loss can range between 3-6 % and 14% annually depending on the site and environmental conditions [2, 3]. Solar glass coatings include antireflection and antisoiling coatings.

In the context of PV modules, soiling loss refers to losses primarily due to dust deposition. Dust includes everything from minute pollen and microfiber to solid soil particles that are airborne. Natural soiling in PV is time-consuming and location specific. The results obtained in natural soiling cannot be generalized due to varying physical and chemical properties of soils across the globe. Hence, there comes the necessity to develop and speed up the soil depositing pattern artificially. Accelerated and artificial means of soil deposition can help reduce the time taken to estimate the losses due to soiling and help authenticate such claims of dust resistant properties and dust removal techniques. Pre-characterized soil from different regions can be deposited using this laboratory-oriented approach, and the losses can be quantified. In addition to the site dependent soiling rate/loss issue, there are increasing number of claims related to dust resistant coating, abrasion resistant (during cleaning) coatings, self-cleaning coatings and new dust removal techniques. Currently, there is no standardized way of verifying the validity of such claims. As a first step towards validating such claims, there is a need to develop a standardized artificial soiling method using laminated module constructions closely replicating actual commercial modules.

Accelerated and artificial means of soil deposition can help reduce the time taken to estimate the losses due to soiling and help authenticate such claims of dust resistant properties and dust removal techniques. Burton et al. from Sandia National Laboratories have reported a means to deposit and characterize artificial soil coatings composed of NIST-traceable dust with known chemical and physical properties [4]. This work attempts to broadly follow Sandia’s procedure but using large area laminated PV coupons and mini-modules that replicate actual module construction and this paper presents an approach for working towards the development of a standardized artificial soiling method.

II. METHODOLOGY

The methodology described here briefly outlines procedure for artificial application of dust on laminated PV coupons and mini-modules so as to measure and characterize the losses in close approximation to the fielded modules with glass / EVA / cell / EVA / backsheet construction.

A. Soil Formulation and Patterning

Soil suspensions were formulated artificially by mixing standardized soil or particulate matter, commonly referred to as Arizona road dust (ISO 12103-1, A2 Fine Test Dust) with HPLC (High Performance Liquid Chromatography) grade acetonitrile. The solution was then sprayed, on the test module using a HVLP (High Velocity Low Pressure) spray gun with a 1 mm nozzle from Central pneumatic. To improve the spray uniformity, a pulse-spray (instead of continuous) approach was implemented. The gun used in the current study has a maximum air pressure of 40 PSI but was used maintaining a constant pressure of 20 PSI. The spray gun allows many adjustments in terms of Fan adjustment, Pattern adjustment and Fluid adjustment. The adjustments were set to spray a fine, round pattern and the fan position horizontal.
Initially the suspensions were prepared to have a composition of AZ road dust mixed with acetonitrile (ACN) in a ratio of 3.3 g to 275 ml. While spraying soil, it was observed that small quantities of soil reached the test module from the gun, resulting in a thin layer of soiling even after many rounds of application. Hence, the composition was changed to 15 g of AZ road dust for every 1000 ml of acetonitrile. Higher concentration of soil in the mixture lead to frequent clogging of the gun.

B. Test Coupons

Polycrystalline and monocrystalline silicon coupons with no AR coating were used in this study. Polycrystalline silicon mini-modules shown in Figure 1(a) of construction Glass/EVA/Cell/EVA/Backsheet with an aperture area of 144 cm² were used. Each mini-module was comprised of 18 polycrystalline silicon cells that are series connected. The dimensions of each cell are 5.7 cm x 1 cm and are rated to produce 1.48 W.

A single-cell monocrystalline silicon coupon with same construction as Poly-Si was used is shown in Figure 1(b). The area of the cell was measured to be 225 cm² (15 cm x15 cm). In order to investigate, the optical properties of soil using spectroradiometer, this coupon was laminated with extra space (3.6 cm) on one edge of the cell to accommodate the reflectance measurement accessory.

C. Artificial Chamber Set Up

To maintain a controlled environment during soil deposition, an artificial deposition chamber was constructed. The chamber consisted of a cuboidal mechanical structure to support an air bag from Sigma Aldrich Corporation. In order to avoid human errors due to hand movement, the spray gun was placed on a mechanical structure and the soil was sprayed. It was observed that increasing the distance increases the uniformity over larger area, while the soil density decreases. Therefore, increasing distance required repeated sprays to attain a desired soil density. The distance between the test coupon and the tip of the gun was maintained at about 2.5 feet.

The artificial chamber was initially erected horizontally, but on spraying soil, it was observed that the soiling pattern was more uniform when the chamber was flipped (placed vertically) and the coupon was placed on the ground, as gravity helps in maintaining uniformity. In addition, it is important to ensure that the spray gun was held perpendicular to the center of the module and a pulse-spray approach was implemented to obtain further uniformity.

D. Soil Density Measurements

The soil density measurements (g/m²) were carried out using commercially available microscope slides (2.5 x 7.6 cm) placed on two sides of the test coupon. The density measurements were obtained using Mettler Toledo (AG285, resolution 0.001 mg). The soil density was calculated by measuring the difference in the weight of the slides before and after soil deposition, divided by the area of the microscopic slide. The average of these measurements was taken to determine soil density on the mini-module.
The measurement procedure uses only two slides as opposed to four slides in four directions. This is because of fan adjustment available in the HVLP gun. If the gun has horizontal fan then, the pattern was observed to be uniform in this axis and the variation, if any, was in the vertical axis and vice versa. This eliminates the need for four slides. Hence, only two slides were used and they were placed in the opposite direction as fan i.e. if fan is horizontal then the slides are placed on vertical axis.

E. Laser Guided Technique

To improve the uniformity, it is imperative to maintain the tip of the gun exactly perpendicular to the center of target area. Initially, soil was patterned on the test coupon/mini-module by holding the gun approximately over center of the test coupon/mini-module. On weighing the microscopic slides, the maximum deviation of up to 0.6 g/m² in density between two slides was found. To increase the accuracy, a laser pointer was attached to the tip of the gun as shown in Figure 3. The laser helped in maintaining the gun over the center of the test coupon/mini-module while spraying, and maximum deviation in density was reduced to 0.2 g/m².

Figure 3. Spray Gun With Laser Pointer

F. Characterization Techniques

This study aimed at understating the effect different soiling densities on performance of the modules. I-V, reflectance and quantum efficiency (QE) characterizations techniques were employed to understand the effect of soiling. The test coupon was initially cleaned with tap water followed by distilled water and isopropyl alcohol. As shown in Figure 4, EL imaging was done on cleaned module followed by IV characterization. Soil layer was then deposited on the test coupon and then soiled IV, reflectance and QE measurements were sequentially carried out. Then cleaned QE and reflectance measurements were taken at exactly the same specific spot by cleaning only that specific region. Two spots per module were selected based on the corresponding EL images.

Figure 4. Flow Chart Indicating the Characterization Process Reflectance and Quantum Efficiency Measurements

A FieldSpec-4 UV-Vis-NIR reflectance spectroradiometer with spectral range of 350–2500 nm from Analytical Spectral Devices, Colorado was used for all the reflectance measurements. It is a compact, portable, precision instrument with fast data collection time of 0.2 second per spectrum. The instrument has a contact probe that is placed perpendicular to the module surface for collecting the reflectance spectra as shown in Figure 5.

Figure 5. Collection of reflectance spectrum

Quantum efficiency (QE) is defined as the ratio of the number of electron carriers generated to the number of photons of a given wavelength that are incident on the solar cell. QEX12M (quantum efficiency measurement system) is a device that can measures QE of a cell within a module using a non-intrusive approach (without cutting the backskin) as well as that of a single cell.

The reflectance measurements were performed on two spots per coupon as shown in Figure 6 and it was ensured that QE was performed on the same spot where reflectance was done.
The soil layer that was present in the spots were cleaned using cotton gauze dampened with isopropyl alcohol.

Figure 6. Soiled Spots Cleaned for Reflectance and QE

III. RESULTS AND DISCUSSIONS

A. Soil Uniformity and Repeatability Check

To check if the soil layer obtained using this approach is uniform, four microscopic slides were placed on four sides of the coupon as shown in Figure 7. A laser-guided technique was used during soil application and the slides were weighed before and after cleaning. The standard deviation for all four soil densities was found to be 0.02%, which is a good indicator of uniformity.

Figure 7. Coupon with Microscopic Slides

Poly-Si modules were coated with different soil densities ranging from 0.6 to 1.55 g/m² as given in Table 1, and single cell modules were also coated with densities ranging from 0.18 to 1.8 g/m² as shown in Table 2. In both cases, similar soil densities show similar $I_{sc}$ losses meaning the process is repeatable. The uniformity pattern was observed in both Poly-Si and mono-Si modules of sample size 144 cm² and 225 cm², respectively. This indicates that the soil spraying process holds good for various size coupons.

![Table 1: I$_{sc}$ LOSS FOR 144 cm² POLY-SI MINI MODULE](image)

<table>
<thead>
<tr>
<th>Mini Module</th>
<th>Soil Density (g/m²)</th>
<th>$I_{sc}$ loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
<td>2.0%</td>
</tr>
<tr>
<td>2</td>
<td>0.80</td>
<td>2.3%</td>
</tr>
<tr>
<td>3</td>
<td>1.08</td>
<td>5.5%</td>
</tr>
<tr>
<td>4</td>
<td>1.55</td>
<td>8.2%</td>
</tr>
</tbody>
</table>

![Table 2: I$_{sc}$ LOSS FOR 233 cm² MONO-SI SINGLE CELL COUPON](image)

<table>
<thead>
<tr>
<th>Single Cell Coupon</th>
<th>Soil Density (g/m²)</th>
<th>$I_{sc}$ loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.18</td>
<td>1.4%</td>
</tr>
<tr>
<td>2</td>
<td>0.34</td>
<td>1.3%</td>
</tr>
<tr>
<td>3</td>
<td>0.62</td>
<td>2.4%</td>
</tr>
<tr>
<td>4</td>
<td>0.92</td>
<td>3.8%</td>
</tr>
<tr>
<td>5</td>
<td>1.57</td>
<td>8.1%</td>
</tr>
<tr>
<td>6</td>
<td>1.80</td>
<td>8.2%</td>
</tr>
</tbody>
</table>

B. Comparison of Test Coupons

Polycrystalline silicon mini-modules and single-cell monocrystalline silicon coupons were used in this study. Here, we compare them to identify the ideal coupon type for artificial soiling and soiling loss characterization.

The uniformity in soiling pattern can be verified using a mini-module. I-V curves were taken before and after soiling on the polycrystalline Si coupon (as multiple cells are connected in series). If there exists any significant non-uniformity, then no smooth curve would be expected between $I_{sc}$ and $I_{mp}$ values.

![Figure 8(a). Circle Indicating Contact Probe Diameter > Cell width for Poly-Si Coupon 8(b). QE Curve for Poly-Si Coupon (1.55g/m²)](image)

Further, uncertainties were observed during the characterization tests of reflectance and quantum efficiency on poly-Si mini-modules. For reflectance measurements, the contact probe diameter of spectroradiometer was found to be larger than the cell width of the polycrystalline mini-module. Instead of covering one cell at a time, the contact probe covered nearly two cells as shown in Figure 8(a). This resulted in some signal noise in the reflectance measurements. When comparing the Quantum Efficiency (QE) measurements for both poly and mono-Si, the influence of grain boundaries on
poly-Si introduced noise in the results as shown in Figure 8(b).

In order to overcome these above stated signal noises and to get accurate measurement results, single-cell monocrystalline silicon coupons was considered as better alternative. All the results presented hereafter in this study correspond to single-cell monocrystalline silicon coupons.

C. Relation between Cleaned QE and Reflectance

As shown in Figure 9, the reflectance drop at wavelength below 1100 nm is due to the cell absorption due to the band gap of 1.1 eV of c-Si cells. The reflectance dip at 1700 nm is attributed to EVA (ethylene vinyl acetate) absorption. If the property of EVA changes over time, then the dip can vary accordingly.

Figure 9. Graph between Cleaned QE and Reflectance for Mono-Si

D. Glass/EVA/Backsheet Reflectance

The white area shown on Figure 10 refers to the area has the formulation of Glass/EVA/White backsheet removing the influence of cell properties in reflectance measurement. The backsheet reflectance decreases as the wavelength increases, and most of the peaks that are seen are mainly due to the backsheet properties as shown in Figure 11.

Figure 10. Contact Probe on White Area for Reflectance Measurements Excluding Cell Area

Figure 11. Reflectance Plot for White Area and White Backsheet

E. Reflectance (Soiled %-Cleaned %) Plots for Various Soil Densities

The reflectance plots for various soil densities ranging from 0.18 g/m² to 1.8 g/m² is shown in Figure 12. From the graph below, it is evident that the reflectance increases as the soiling density increases. For all soil densities, maximum reflectance was found to be between 400-1100 nm, which corresponds to the absorption region of c-Si cells.

Figure 12. Reflectance (Soiled %-Cleaned %) Plots for Various Soil Densities

F. Particle Size Effect on Reflectance

When comparing the outdoor natural soiling reflectance [5] with indoor artificial soiling reflectance [this study], the differential reflectance curve over the absorption region of c-Si (circled) is nearly constant (flat) for outdoor soiling as shown in Figure 13 and it is not constant (not flat) for indoor soiling as shown in Figure 14. Bowers et al. showed that reflectance increased with a decrease in particle size and this effect was more prominent for a particle size less than 400 microns, which is possibly true in the case of indoor soiling [6]. As wavelength decreases, the scattering increases. The scattering effect due to fine particle size could be the reason for non-flat reflectance observed in indoor reflectance measurements.

Figure 13. Outdoor – Differential Reflectance Plots at Various Soil Densities
G. Reflectance Measurements – A Measure of Soiling Density

Delta (soiled %-cleaned %) for indoor reflectance measurements is calculated for each soil density. The slope of the data is calculated and the R² value is determined for all the wavelengths ranging from 400 to 2500 nm. The wavelength between 600-700 nm showed an acceptable R² value of 0.918. Similarly, for outdoor soiling, the wavelength between 600-700 nm was determined to be a good fit, irrespective of the technology for measuring density. The following equation can be used to determine the soil density if the reflectance is measured before and after cleaning the soil layer:

\[
\text{Soil density (g/m}^2\text{)} = 25.35 \times \text{average reflectance loss (%)} - 0.36 \quad (1)
\]

The correlation plots between QE and soil density shown in Figure 15(a), and reflectance and soil density shown in Figure 15(b) are linearly related. This study indicates that the soil density can be calculated just by measuring the reflectance without the need of collecting soil samples from the solar glass surfaces. Once the soil density is known, the energy loss (Iₜₜ loss) can be calculated as discussed above.

IV. CONCLUSION

Major conclusions resulting from this study are as follows:

- Gravity-assisted and laser-guided approach of spraying soil onto coupons helps in improving the soil uniformity pattern; total area of the test coupon for soil application can be increased by increasing the distance between the module and spray gun.
- Mini-modules can be used to check uniformity by measuring I-V curves, wherein, for characterization tests including QE and reflectance, single-cell mono-Si coupons are more favorable.
- Properties of encapsulant (EVA) over time can be determined by carrying out reflectance measurements.
- Particle size can play an important role in reflectance measurements. The smaller the particle size, the higher the reflectance. Also, scattering effect is dominant for smaller particles.
- Reflectance loss can be used as a direct measure of soil density.
- Soil density can be used to calculate the Iₜₜ loss (or energy production loss) in PV power plants.
- The lessons learned from this study would be useful toward the development of a standardized artificial soiling method.

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REFERENCES