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FIELD EXPERIENCE: THE USE OF SPECTROMETRY FOR SOILING ANALYSIS ON PV

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Abstract: Soiling or dust accumulation on photovoltaic solar modules deters the transmission of irradiance through the glass surface covering of the modules. Spectrometry is suggested as a manner to determine the true change in transmission as a result of the accumulation of dust. This study in form of a field experience shows how spectrometry could be used to collect detailed data in the field regarding the environment and its effect on the modules. This study also suggest how spectrometers should be applied in field experiences to ensure accurate and meaningful measurements. It was found that the clean glass module covering induced irradiance transmission losses approximately 7% in the spectral band 620-920 nm. Minimal, barely visible soiling, characterized as a dust-water solution caused an additional 2% loss over solar noon in the spectral band 320-920 nm.

Key words: Spectrometry, PV, soiling, spectral response, solar, field experience.

1. INTRODUCTION

The quality of air is aggravated by natural and increasingly, human processes. These suspended particles are known to deposit on photovoltaic (PV) modules, varying in amount as meteorological conditions vary. From research available on the adverse effects of dust deposit on PV modules, it is anticipated that dust is detrimental to solar performance, especially in arid environments which is characterized by high variability in rainfall and large quantities of dust carried from surrounding areas (Aeolian dust). For methodological purposes, dust is used as a common term for particles with a diameter smaller than 500 microns [1]. The deposition of particles is also often referred to as a "soiling" effect [2].

It is expected that deposited particles on modules interfere with spectral transmission by mitigating and scattering irradiance [3]. This can also be described as extinction: the beam of light, or radiation, is scattered and absorbed by these small particles which decreases beam intensity. The incident angle of radiation will noticeably affect the module efficiency and it will enhance extinction due to dust. The amount and size of these particles depend on the environment in which it is located. Sarver [1] found that the deposition of finer dust, versus coarser particles, has a greater adverse effect on module performance. Fine particles have the tendency to distribute more uniformly, whereas larger particles leave beneficial voids where light can still pass through. [1]. It is also true that the type of particles that deposit on modules depend on the deposition mechanism, determined amongst other by the tilt angle of the surface. For example, a horizontal surface will collect larger particles since the principle mechanism is gravitational settling; a vertical surface might collect finer particles through diffusion [2].

Presently, the impact of this soiling on PV module output is primarily investigated through short-circuit current measurements and output efficiency [3–5]. Quantifying the effect of soiling in this manner is challenging since associative effects of the inherent module characteristics, cell type and environmental factors, such as temperature, frequently influence the output of modules. Since data may be skewed by these associative effects, a large amount of modules over a longer period of time is required to first understand the inherent characteristics of the module before a true soiling analysis can be performed. Solar radiation simulation and dust depositing laboratory type experiments [6,7] are becoming more common, since these investigations allow for very controlled circumstance and reckonable variables. However, it can be argued that these controlled environments are not true representations of soiling; in the field, soiling quality and quantity is weather dependent, which is variant in nature.

Traditionally in PV research, solar irradiance transmission through the atmosphere is measured either by a pyrheliometer for direct radiation measurements or a pyranometer for diffuse and global radiation measurements [8]. These measurements supply the power density for a defined area - the amount of irradiation in W/m^2. To determine the spectral content of this incident light a spectrometer is required. Predominantly spectrometry is applied to the analysis of absorption, reflectance and transmission [9]. These types of measurements are well suited to laboratory studies, but field spectral measurements are observed in oceanography [10], atmospheric studies [11] and other fields of biology, physics and chemistry [12]. Using optical spectrometry, the associative effects of the PV module are curtailed since the analysis is done separately on the glass covering of the module. These measurements are taken to the field to investigate real life scenarios of radiation and dust depositing. The measurements collected not only characterize the spectral response in accordance to the effect of dust but also supplies the spectral distribution of irradiance incident at varying moments in time.

In this work we introduce equipment which is not usually used in PV field research - to identify the limitations and requirements of the spectrometer in this field. This experience also creates the opportunity to determine measuring details such as the field of view, measuring angle, environmental reflections and the equipment response - it is also a preliminary collection of data with two different spectrometers. Spectrometry creates a new way of measuring the change in irradiance transmittance as a result of soiling and properties of the module glass.

2. EXPERIMENTAL SETUP

The field experiment consists of non-automated measurements with two different spectrometers - these measurements can be called spetroradiometry since it entails the measurement of radiant power impinging on a surface per unit area in the UV, VIS and NIR wavelength ranges. The use of two distinct spetrometers allow for comparison of instrumentation but more importantly for confirming measurement results.

Measuring irradiance allows for determining the loss in transmission of the module glass as well as the effect of soiling, or dust accumulation. Characterizing the nature and amount of dust in the field is complicated - spectrometry eliminates the need for specific characterization by presenting the direct effect of soiling through a comparison of measurements.

2.1 Spectrometers

Table 1 gives an overview of the technical difference between the two spectrometers used in the field experience. This does not however give a representation of the true variation in the instrumentation. Figure 1 is a plot of data measured by the two spectrometers, 3 minutes apart, at the exact same position, angle and an 180°field of view.

Table 1: Spectrometer Technical Details

Variable	**BLUE-Wave StellerNet**	**PSR-1100F Spectral Evolution**
Detector	2048 pixels	512 pixels
Digitizer	16-bit	16-bit
Range	278-1100 nm	320-1100 nm
Slit Size	25 μm	50 μm
Resolution	1.0 nm	<= 3.2 nm
Integration Time	1-6500 ms	8-2000 ms

All spectrometers have an optical component that diffracts incoming light into several beams - the diffraction grating. The directions into which these light beams are diffracted depend on the wavelength of the incoming light as well as the spacing of the gratings. The resolution increases as the number of grating lines decrease, with the disadvantages that the wavelength range decreases. Both spectrometers are factory-calibrated for irradiance using a NIST-traceable source.

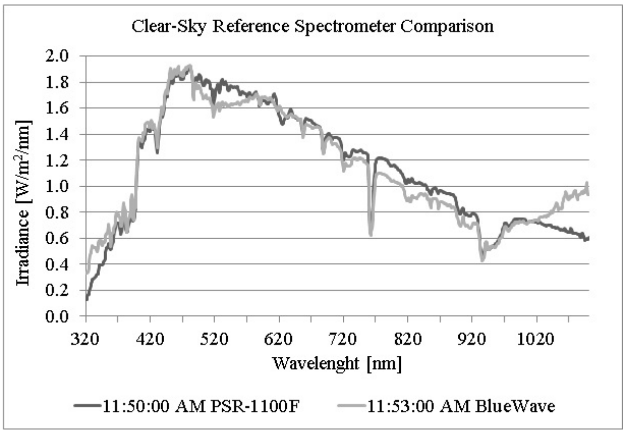

Figure 1: Clear-sky reference comparison measurement of two spectrometers at approximately 11:50

The spectral curves shown in Figure 1 are similar, but two varying markers are defined: the approximate band 500-580 nm shows an unexpected dip and an unexpected increasing trend in 1020-1100 nm, both in the BlueWave spectrometer plot. Both these markers are ascribed to the sensitivity of the instrument - these measurements were taken with temperature compensation activated, causing some signal distortion at the peak irradiance and higher spectral bands.

Although the solar spectrum constitutes of wavelengths 0.2-2.5 microns, the longer wavelengths are limited by the band gap of the cell material and the short waves are limited by material absorption [13]. Hence the wavelength range relevant for PV performance is limited to approximately 0.3-1.1 microns, which is in good co-ordinance with the range of the spectrometers used.

The glass used are a full size PV module glass supplied by First Solar, and a smaller low-iron float glass sample with similar characteristics to the PV module glass. The PV module glass has a thickness of 3 mm, while the low-iron float glass has a thickness of 4 mm.

2.2 Measurements

The irradiance transmitted through two different types of glass samples was measured and compared to non-obstructed reference measurements. On the full size PV module glass, four consecutive measurements are performed within one minute: a clear-sky reference measurement, a clean glass measurement, a dirty glass measurement and a second clear-sky reference measurement. The second reference measurement is used to determine the stability of irradiance - to confirm stable conditions. Similarly, on the small low-iron float glass, three consecutive measurements are performed: a clear-sky reference, small glass and a second clear-sky reference measurement. These measurement sets were repeated with intervals of approximately 30 minutes. As clouds may cause rapid variations in irradiance, the measurements are performed on clear-sky days.

The setup is in the field is shown in Figure 2. The frame on which the glass is mounted has an altitude angle of 30°and the frame face towards magnetic North. The measurements were performed in a fixed position, parallel to the glass - however, as the spectrometers are hand-held some discrepancy in measuring angle is expected.

Figure 2: Glass frame for experimental setup with solar glass permanently mounted to the right pane and temporarily mounted low-iron float glass pieces in the centre pane

As a side note; it was expected that the field of view would have a significant effect on the measured data and this was confirmed by measurements with a receptor of 5°and 25°field of view on the PSR-1100F spectrometer. The measured data was inconsistent to what was expected and shown by the 180°field of view measurements. The inconsistency for the 5°field of view could be ascribed to the dependency on lens position - the data collected had higher values with the clean solar glass and lower without. The inconsistency for the 25°field of view is less systematic and variates with each measurement.

3. RESULTS

3.1 Irradiance Measurements

Clear-sky measurements are used as reference measurements to ensure that the experiment is completed under stable conditions but moreover it allows for the characterization of spectral phenomena and confirmation of instrumentation - does the measured data correspond to what is known about spectral variation.

Figure 3 shows clear-sky spectrums with different time stamps, measured on October the 17th. The solar spectrum distribution is characterized significantly by absorption and reflection. Ozone absorbs significantly at wavelengths shorter than 0.4 microns [9], whereas water vapour has absorption bands in NIR and SWIR, with the first absorption band at 1.36 microns, which falls outside the rand of interest for this research. Still, the effect of absorption is substantial and therefore the solar zenith angle is a critical parameter. The air column density increases as the zenith angle increases from the vertical - therefore the water vapour increases [9]. At a large zenith angle, for example at 09:00, the amount of water vapour in the path of radiation is still significant and might increase variability and distortion in spectral measurements. Therefore, air mass (AM) has a noteworthy influence on spectral variation. This spectral variation is also noted throughout the year because of the Earth's elliptical trajectory.

As previously explained, the sun position and AM is an indication of the amount of irradiance expected throughout a day - it is expected that the afternoon measurements will have a higher average irradiance than morning values, but Figure 3 shows that the irradiance measured at 15:34 is lower than at any other time throughout the day. The BlueWave spectrometer showed the same discrepancies but the spectral curves measured does adhere to the ASTM G173-03 reference spectra curve with the assumed topographical markers for absorption bands and Fraunhofer lines [14].

In winter months the solar radiation path to the ground is increased, or rather the AM is increase, and a range increase in the higher wavelengths has been observed (aka a red shift) [15]. Similarly it can be expected that the observed spectrum will be more red in the mornings and bluer in the afternoon.

As previously mentioned, spectrometry gives an insight to the spectral distribution of radiation - specifically the direct beam radiation when it it is directed towards the sun location. Measurements taken on another clear-sky day in July showed what was expected with lower average irradiance values in the morning, becoming increasingly higher until approximately 15:00, where it started to decrease again. Although, as expected, the average irradiance is lower since the measurements were completed in winter months; still it is observed that the at 15:00 the average irradiance is higher than that at 09:02 - unlike what is observed in Figure 3. The difference between these two sets of measurements are the measurement direction - the second being direct beam irradiance which can only be correctly measured when light is collected directly in position with the sun.

Therefore, the discrepancies viewed in Figure 3 can be ascribed to the measurement relating to the sun position. It can also be said that the frame in which the glass was mounted had an adverse effect on the measurements since it caste a shadow over the measurement area.

Figure 4 and 5 show the difference between two reference spectra in the morning and afternoon, respectively. The reference are used to evaluate that hte irradiation conditions are stable, and hence that the measurements performed between the two reference spectra can be compared directly. Conditions are considered stable when two baseline direct beam irradiance measurements with an 180°field of view within 1 minute differ less than 5 %. As expected, Figure 4 and 5 confirms that spectral variation is less around noon. These two percentage change plots are a summary of the spectral variance as measured by the BlueWave spectrometer throughout the day. The spectral discrepancies in the BlueWave spectrometer measurements does not effect this conclusion.

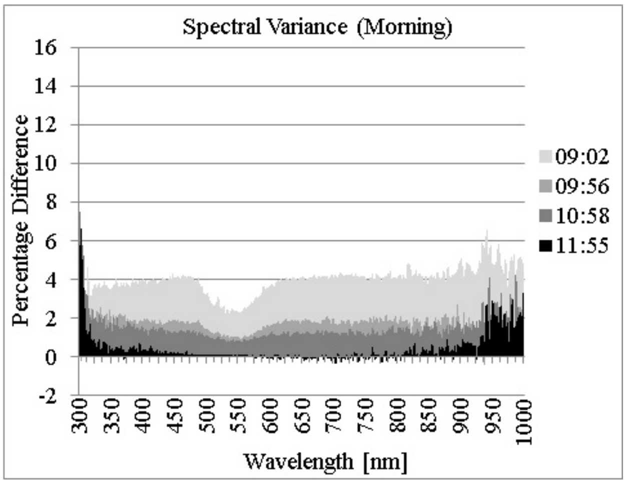

Figure 4: Percentage change in reference measurements across the spectrum, BlueWave spectrometer

It is anticipated that clean glass should influence the measured irradiance - this transmission loss is due to reflection on the glass surface and absorption within the glass due to iron impurities. The glass is classified as clean when it is wiped for any visible particles but not polished to remove minor scratches and finer imperceptible particles.

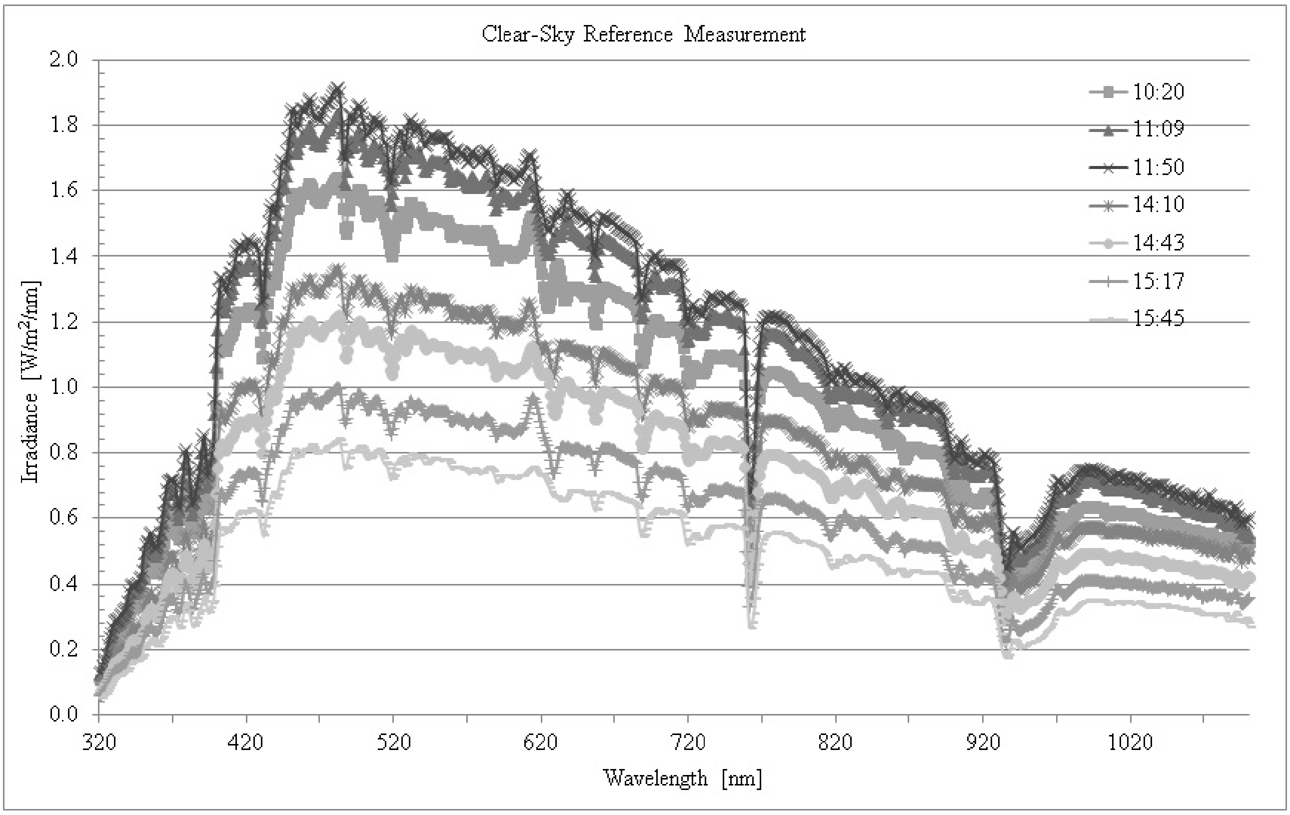

Figure 3: Clear-sky irradiance measurement altitude 30°and azimuth 0°, PSR-1100F spectrometer

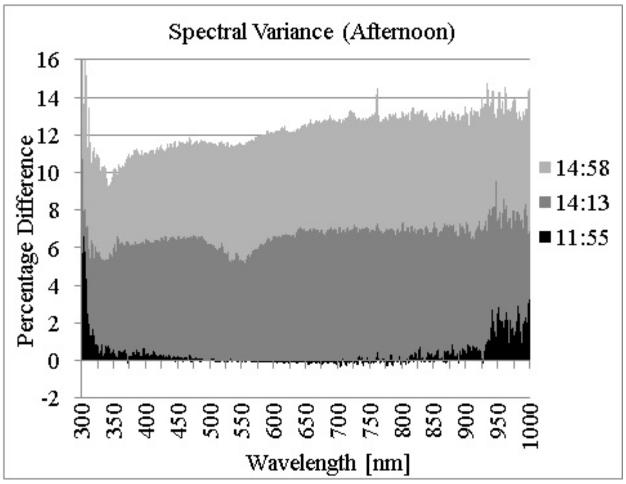

Figure 5: Percentage change in reference measurements across the spectrum, BlueWave spectrometer

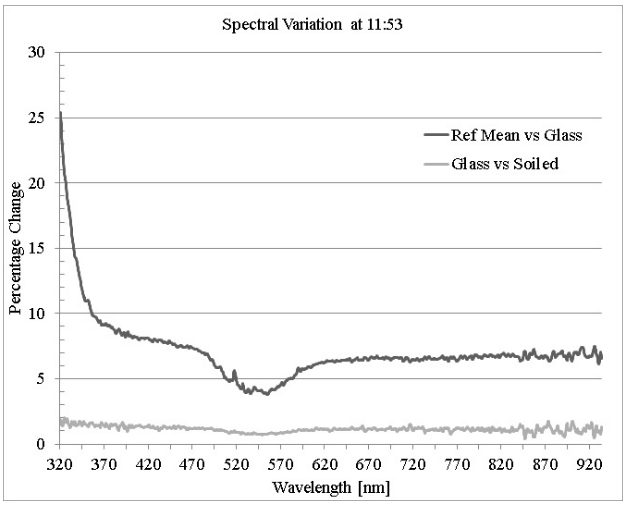

Figure 6: Percentage change in a measurement set around noon for the solar glass, BlueWave spectrometer

Determining the effect of soil particles on direct beam irradiance is complex since additional particles cause complex refraction, reflection and absorbance of light beams. Also, categorizing the amount of particles and the distribution thereof is not a precise science when particle distributions is by natural methods - which is the focus of this study. In this field experience the "soiled" glass referred to in section 3.2 is soiling from approximately 3 days in which strong wind gusts and a few large rain drops where present. Some soiling can thus be attributed to a water-dust combination but this is only slightly visible.

3.2 Large Solar Glass

Figure 6 shows the difference in irradiance between the reference measurements and the clean module glass, as well as the change between the clean module glass and the slightly soiled glass. The wavelength range shown has a variation in reference irradiance of less than 1%. Since spectral variation was confirmed to be more stable around noon, the measurements performed at 11:53 was used in this analysis.

The spectral discrepancies measured by the BlueWave spectrometer is also visible in this plot. The 500-580 nm band causes a valley in both plots in Figure 6. The spectral band below 320 nm, and above 920 nm is not shown in this plot since it is greatly influence by the sensitivity of the instrument causing spectral variation of more than 1%.

3.3 Small Low-Iron Float Glass

Figure 7 shows the difference in irradiance between the reference measurements and the irradiance through the small low-iron glass sample. Although the curve is similar, the low-iron float glass have a higher average change than the solar glass; the low-iron float glass have an approximate 8% reduction in irradiance transmittance in the waveband 620 - 920 nm. Similarly, the BlueWave spectrometer measurement discrepancies are observed.

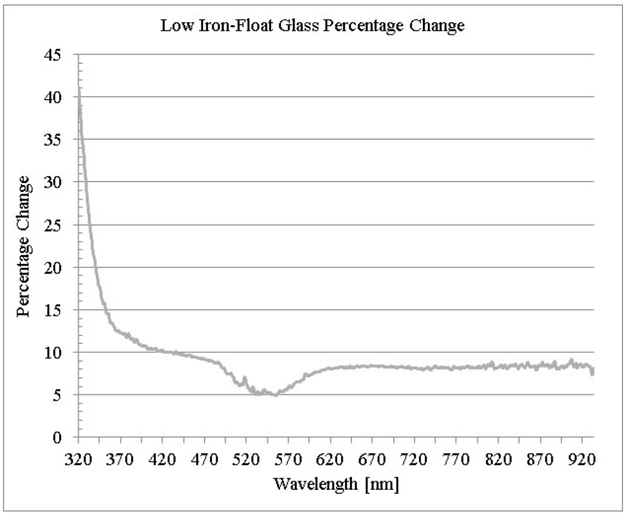

Figure 7: Percentage change in a measurement set around noon for the low-iron float glass, BlueWave spectrometer

Although the larger part of the spectrum is reduced only 1% more by the low-iron float glass than the true solar glass, in the approximate band 320 - 420 nm, the low-iron float glass does reduce transmission more. This band has a peak transmission loss of approximately 39%. This should be taken into account when further experiments are completed with the low-iron float glass - which is included in the field experience for the usefulness of size in further lab research.

4. CONCLUSIONS

This field experience has brought to the attention the specifics of field spectrometry measurements to determine the transmission loss of irradiance by solar glass, as well as soiling.

The specifics of field spectrometry measurements refer to:

1) The dependence on sky-conditions - limiting the chance of spectral variance when measurements are completed to reduce the amount of environmental variables which could influence the spectral measurement; measuring on clear-sky days around noon will allow for the least spectral variance and therefore most accurate transmission loss results.
2) The spectral instrumentation, spectrometers, supply detailed spectral information. Comparing measurements from two different instruments are complex since instrument sensitivity and accuracy differ and ensuring that the measuring circumstances are identical in field measurements are impossible.
3) The signal detected by the spectrometer can be influenced by multiple sources - unnatural environmental reflection (such as the frame on which the glass is mounted), ground reflection at the back of the glass which is impossible in a solar module and the angle at which the receptor is in regards to the glass, as well as the receptor angle in regards to the sun location.
4) As characterizing dust is complex and a spectrometer's receptor only measures a certain area on the soiled glass, it does not give a true representation of the soil character of the total piece of glass but only a localised transmission loss result.

A suggestion would be to automate this field measurement - this could bring solutions to all four specifics mentioned above. This would also supply more information regarding the characterization of the glass, the influence of cloud cover and the influence of the angle of incidence on the transmission through the glass and/or soiling.

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