Spectral Rear Irradiance Testing and Modeling for Degradation and Performance of Solar Fields

Preprint

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Spectral rear irradiance testing and modeling for degradation and performance of solar fields

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***Abstract*—This work investigates how the spectrum of irradiance incident on the rear of solar modules impacts the degradation and performance of backsheets. We model the spectral irradiance incident on the rear of modules through raytrace simulations and validate with measured field data collected from a 75kW single axis-tracked bifacial test site. A generic equation to estimate relative degradation is proposed, and we show that current acceleration factors for UV damage in chambers can be sub-estimate up to 4.5% absolute from the usually assumed 10% dosage on the rear surfaces.**

Keywords—solar PV, rear irradiance, UV degradation, bifacial performance

I. INTRODUCTION

In 2021, ~90% of the photovoltaic (PV) modules in the field were less than ten years old. There are significant unknowns regarding the durability of new technologies and materials being deployed without established performance histories. While accelerated testing attempts to capture degradation modes, the fast roll-out of new materials poses a challenge resulting in high probabilities of false-negative or false-positive results. In particular, the aging behavior and failure modes of backsheets is of interest to ensure PV modules' performance. Current degradation testing for backsheets commonly assumes 10% of UV dosage on the back relative to the front. This study explores that assumption.

Light on a module's front side comes primarily from direct solar irradiation, some diffuse scattering from the sky, and small contributions from light scattered from ground sources. In contrast, light incident on the rear of PV modules may have no direct irradiation and only a smaller portion of diffuse light from the sky. Here, a significant amount of light comes from reflection from the ground, mounting structures, and other nearby objects. However, most surfaces have lower reflection in the UV range relative to visible light. This causes the intensity and spectrum to be significantly modified relative to the front side exposure (Fig. 1). However for special cases such as snow, measurements not only have a stronger spectral content but also appear 'blue-shifted' as there is less absorption in the NIR and VIS spectrum. As a result, UV-irradiance levels and resulting degradation experienced by PV backsheets is dependent on the mounting structure of the array, the location of the modules within the array, the environmental albedo and weather conditions including temperature, and spectral direct normal irradiation (DNI) and diffuse horizontal irradiance (DHI) characteristics. In the context of bifacial PV, it has been shown that spectra reflected from different ground materials may cause variations between power output predictions and measurements of up to 3.1% for grass or 5.2% for sand [1].

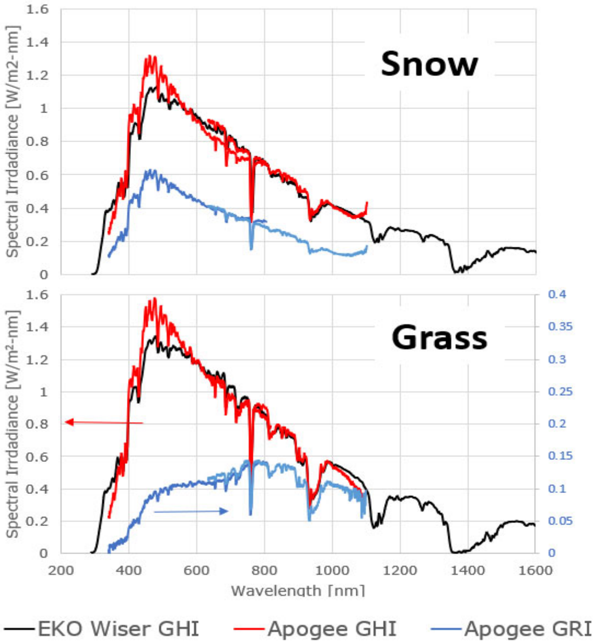

Fig. 1 GHI and Ground Reflected Irradiance spectral irradiance. Apogee instruments were taken in the field at noon with horizontal tilt, and the EKO wiser was located nearby at the SRRL. The ground snow measurements not only have a stronger spectral content but also appear 'blue-shifted' as there is less absorption in the NIR and VIS spectrum.

UV induced degradation modes typically occur more readily at lower wavelengths where the photon energy is higher and absorption is stronger. To understand the impacts of the albedo on degradation, the reflectivity of materials in the PV field and the spectral distribution of direct and diffuse light in the UV-spectra are essential. The raytracing tool used for modeling front and rear irradiance in PV modules bifacial_radiance has been modified for spectral calculations as part of this project. Raytracing results are compared to field degradation in a PV array in Maryland, MD [2]. Field measurements by different narrow- and broadband irradiance sensors and spectrophotometers taken at the 75-kW single-axis tracked bifacial field at the National Renewable Energy Laboratory (NREL) (Golden, CO) are also used to validate the methodology described below [3].

II. METHODOLOGY

A. *Degradation Calculation*

The degradation (D) experienced by the backsheet material can be modeled as a function of time *t* and wavelength λ with the empirical formula:

$$D = D_o \int_0^t RH(t)^n \cdot e^{\frac{-E_a}{RT(t)}} \int_\lambda \left[e^{-C_2\lambda} \cdot G(\lambda, t)\right]^x d\lambda dt, (1)$$

where $T(t)$ is temperature in Kelvin at a specific hour, λ is the wavelength, E_a is the activation energy, R is the universal gas constant, RH is the relative humidity, *n* is a coefficient denoting the sensitivity of the material to humidity, C_2 is the coefficient for the exponential degradation of the material as a function of wavelength, $G(\lambda)$ is the irradiance in W/m^2 at the specific wavelength, and *x* is the scaling of the degradation effect due to irradiance intensity. Eq 1 is just one of many different functional forms for degradation in response to UV light. Furthermore, this can model only one degradation mechanism and is an empirical function. For C_2 and *x*, both the functional form and the values are empirical. However, from surveying many different degradation processes, we know that values between $x = 0.64 \pm 0.22$ [4] are common and that C_2 is commonly around 0.07 (1/nm) [5]. The activation energy for UV processes is typically around 40±15 kJ/mol. For humidity, the dependence can be nonexistent (*n*=0), negative or positive, and is set to n=1.0 for this paper calculations. This provides a basis to begin to characterize the relative degradation expectations of the backsheets in different environments and mounting configurations relative to the frontsheet degradation as,

$$D_{ratio} = D_{rear} / D_{front} \qquad (2)$$

To describe the degradation on the backsheet, one must know the spectral distribution and intensity of light on the backside of the module as a function of time with corresponding meteorological data. By considering the relative degradation one can minimize the issues with temperature and humidity dependence, and can ignore the prefactor D_o of Eq. 1. It is far easier to make comparative assessments than to predict actual degradation rates.

B. *Rear Irradiance Modeling*

The Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS2) [6] was used to generate spectral DNI, DHI, and global horizontal irradiance (GHI) and spectral ground reflectance for various ground types. This tool generates clear-sky irradiance spectra. The spectrum between 300 and 2500 nm was considered for the simulations. A method to correlate field measurements of DNI, DHI and GHI with the spectra generated by SMARTS was implemented so that

$$E^*_{scaled}(\lambda) = \frac{E_{meas}}{\int E^*(\lambda)\, d\lambda} \times E^*(\lambda) \qquad (3)$$

In this equation, $E^*_{scaled}(\lambda)$ is the resulting scaled irradiance spectrum, E_{meas} is the field measured irradiance value, and $E^*(\lambda)$ is the modeled irradiance spectrum from SMARTS. This methodology is valid only for mostly clear skies, as the scaling does not alter the relative spectral distribution of the components. Ground reflectance spectrum is generated depending on the type of ground cover most common in the season (dry or green gas), and high sustained albedo values (>0.5) are generated as snow albedo. Ground-reflected spectra are likewise scaled to match field-measured albedo values with eq. (3).

C. *Rear-side Irradiance and Degradation Measurements in Gaithersburg, MD (NIST Site)*

The degradation patterns and gradient irradiance conditions in the rear of the modules were published in [2] for a PV array in the National Institute of Standards and Technology (NIST) campus in Gaithersburg, Maryland (USA). In the NIST site, the edge module degradation effect observed for yellowing and gloss appears similar to irradiance's measured patterns. The conditions and geometry of the site were modeled for April 28th 2017, reproducing Fig. 5 from this paper and the degradation for a typical model year was calculated.

D. *NREL Spectral Irradiance Measurements*

Meteorological and spectroradiometer data were measured for one day with calibrated sensors 0.5 km distant from the bifacial horizontal single-axis tracker field (HSAT) at NREL's Solar Radiation Research Laboratory (SRRL)[7]. Ground-Horizontal Spectral irradiance is measured at the SRRL at NREL using an EKO WISER spectroradiometer, with a frequency response between 290-1650nm. Plane of Array spectral measurements were taken in the bifacial field with two co-located Apogee field spectroradiometers – the SS-110 with sensitivity from 340 nm to 820 nm and the SS-120 with sensitivity from 635 nm to 1100 nm (Fig. 3b). Both instruments were calibrated against the higher-accuracy EKO unit at the SRRL. Front and rear POA were also measured with Silicon reference cells (IMT).

III. RESULTS

A. *Gaithersburg, MD (NIST Site)*

As expected, there are PV array edge effects (Fig. 2a) seen through modeling the NIST PV array in addition to shading effects that vary the irradiance across the collector width. Comparing the modeled to measured irradiance, the absolute root mean square error is less than 10 W/m^2. This is within the range of uncertainty for a photodiode measurement used by Fairbrother et al. [2]. Uncertainty in the measurements is further exacerbated by the position they were taken during the field survey. As shown in Figure 2b, the beams contribute to a shading factor of 13.7%. However, depending on where the measurement is taken, the irradiance level can be reduced to half or increased to 3x higher than the average.

Table 1 shows the relative degradation of the backsheet versus the front of the module as computed using Eq. 4. For the hour modeled, the top of the edge modules in the center row experience 75% more degradation than the middle of the center module of the array, or 4.5% absolute more degradation than the 10% assumed on back sheets. Edge effects of the module itself also represent a 20% increase in degradation in the top of the modules relative to the center

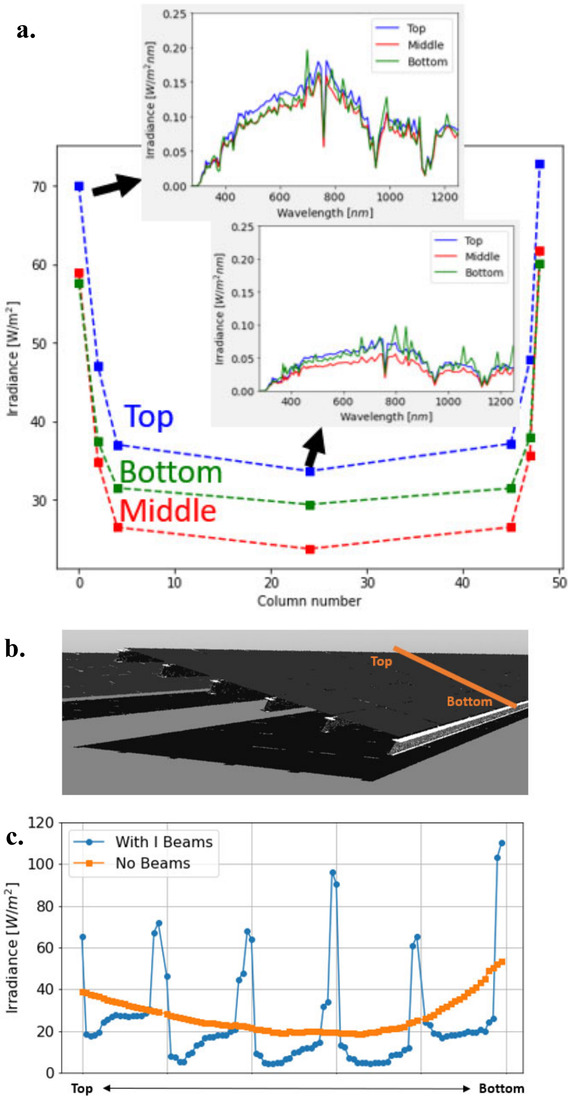

Fig. 2. a) Modeled spectra and the integrated irradiances for the rear of the central row of NIST array for 04/28/17 at 12 PM. b) Computer simulation model of the array. c) Rear irradiance across the central module, showing specular reflections and shading from the I Beams (shading factor of 13.7).

TABLE I. DEGRADATION RATIO

	Degradation Ratio (back/front * 100%)			
Sensor Location	Center Row, West Edge	Center Row, Center	Center Row, East Edge	Southern Row, Center
2 (top)	14.5	9.9	14.4	10.0
1 (middle)	13.3	8.3	13.1	8.4
0 (bottom)	13.0	8.6	12.8	8.9

Spectral effects of albedo have been studied in [8], pointing to how different sensors affect measured ground reflected irradiance. The absorption effects of ground are difficult to isolate in spectral measurements because there can be a competing enhancement of irradiance resulting from multiple reflections between the sky, clouds, structures in the PV field, and the ground surface itself. Fig. 3b shows a rear-spectral irradiance measurement and model in the tracker field. There is good agreement on wavelengths of interest for degradation (< 450 nm). Modeled and measured integrated values of the rear-POA spectra fall in the uncertainty range of the IMT-reference cell.

IV. CONCLUSIONS

We propose a method to calculate relative backsheet degradation. This is enabled by raytracing, showing that while rear irradiance can be below 10% of the front irradiance, spectral effects lead to higher degradation ratios than the 10% currently used in accelerated testing. The full manuscript will expand on this proceeding results.

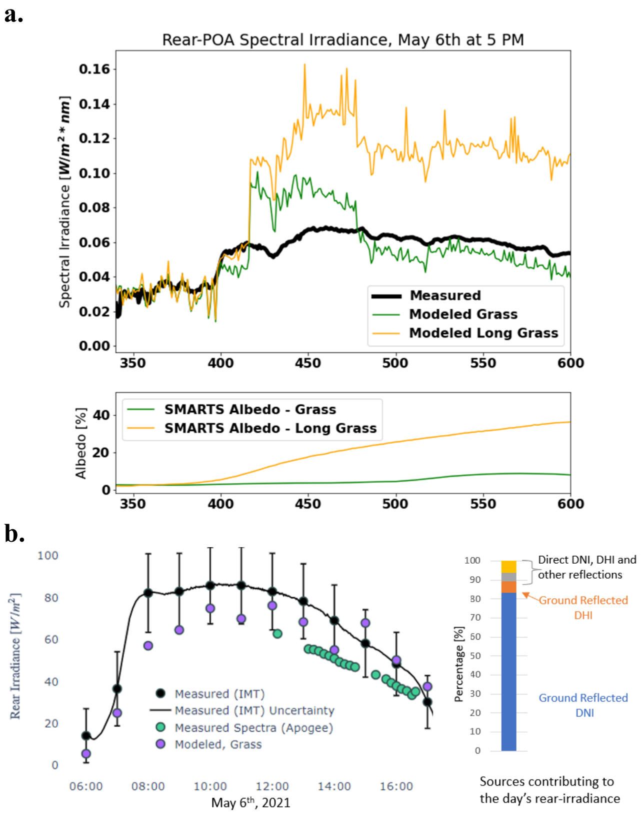

Fig. 3 a) Spectral rear irradiance measured and modeled on the rear-side of the HSAT, east-most edge at 5 PM. b) Modeled and measured spectral integrated spectral irradiance, compared to the measured IMT irradiance and it's uncertainty. (right) Shows the contribution of ground reflected DNI and DHI, versus direct DNI, DHI and other secondary reflections.

REFERENCES

[1] Russell (2017); [2] Kim (2018); [3] Fairbrother (2018); [4] BEST Field Data 2020; [5] Fischer [2004]; [6] Miller (2009 [7] Gueymard (1995); [8] Stoffer (1981); [9] Gostein (2021)