UV Degradation in Backsheets: a ray-tracing irradiance simulation approach

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Introduction

Around 90% of current photovoltaic (PV) modules are less than ten years old. New PV technologies and materials are deployed without documented durability and performance histories. Accelerated testing attempts to capture degradation modes but rapid rate of development of new materials results in bad materials occasionally being used. Current testing assumes UV damage on the rear of a module to be 10% of that incident on the front.

We present a method to quantify UV degradation on PV backsheets in the field. We aim to evaluate if current acceleration factors for UV damage in chambers are properly estimating degradation for different PV sites and different mounting configurations. This method leverages *bifacial_radiance* to ray-trace and evaluate irradiance on the front and the rear of the modules. Then an equation to estimate the relative degradation is proposed.

Methods

The degradation (D) experienced by the backsheet material is often modeled as a function of time t and wavelength λ, such as:

Relative Humidity

Spectral Irradiance [W/m²nm]

$$D = C\int e^{\frac{-E_a}{RT(t)}} RH(t)^n \int [e^{-C_2\lambda} G(\lambda,t)]^x \, d\lambda dt \qquad \text{Eq. 1}$$

Arrhenius Equation

Exponential Degradation as a function of wavelength

This requires modeling or knowing *RH* is the relative humidity within the material, the temperature of the cell or module and the spectral irradiance G [W/m²/nm] received by the backsheet. The pieces to these are explored in the next column.

	Description	Typical Value(s)	Ref.
E_a	Activation Energy	40±15 kJ/mol.	
n	coefficient denoting the sensitivity of the material to humidity	1.0	
C_2	Empirical coefficient for the exponential degradation of the material as a function of wavelength	0.07 (1/nm)	[1]
x	and is the scaling of the degradation effect due to irradiance intensity	$x = 0.64 \pm 0.22$	[2]

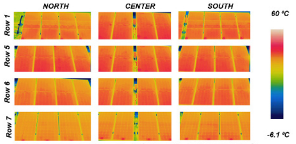
As a basis to begin to characterize the relative degradation expectations of the backsheets in different environments and mounting configurations, and in comparison to the frontsheet degradation we use.

$$D_{ratio} = D_{rear}/D_{front} \qquad \text{Eq. 2}$$

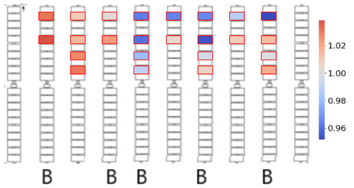
Methods

Temperature Model

Attempted to find correlation between temperature and position in module with IR measurements at the 75kW HSAT array at NREL [5]. Handheld irradiance sensors not optimal for this evaluation.



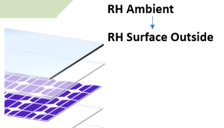
May 20th, Temp. Air: 28 °C DNI 930 W/m²
Wind Speed: 3-5 m/s @ 200-260° (E to SE)



Module temperature variations for a year for monofacial and bifacial modules, normalized to the average of the field. No pattern detected for module's place on the row or array

Using PVLib [6] Module Temperature model, with different values calculated per module based on averaged irradiance.

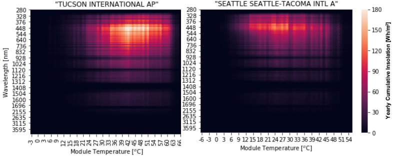
RH Model



Once the module temperature is determined, the saturation point of the module is calculated and used to determine the RH at the surface of the module[4].

Spectral Model

Using python SMARTS wrapper [6] on Github.com/NREL/pySMARTS



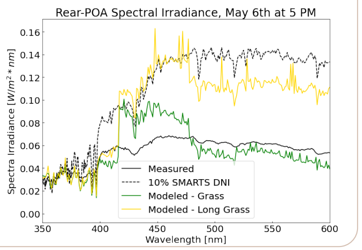
Spectral Irradiance calculated using SMARTS [7]. Shown here is the insolation by wavelength for the year, binned by ambient temperature

Spectra for use on the simulation is weighted by field measurements of DNI, DHI, and albedo [8]. This Method is only applicable for mostly-clear skies as it does not modify relative spectral contents for clouds.

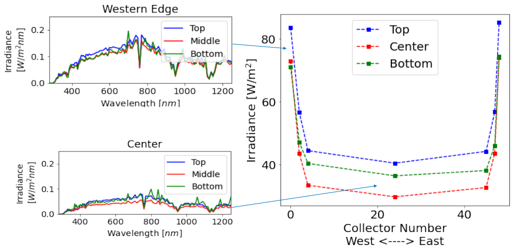
$$E^*_{scaled}(\lambda) = \frac{E_{meas}}{\int E^*(\lambda)\,d\lambda} \times E^*(\lambda)$$

Rear Irradiance Modeling

Front and Rear Plane of Array spectral irradiances (POA) are simulated by wavelength for specific locations across an array with bifacial_radiance. Results can be integrated to obtain Irradiance. Contributions from the ground-reflected, direct irradiances are also evaluated (for non-spectral simulations).



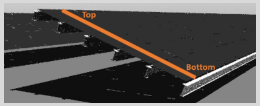
Results

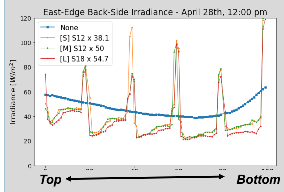


Validation with NIST array (Gaithersburg, MD)

Rear POA measurements from a fixed tile array around noon 04/28/17 [9] were compared to spectral simulations. The modeled values are in the range of uncertainty of the sensors.

Irradiance and degradation edge effects are present in the edge modules, both in measurements and simulations. The array's edge modules receive up to 81% more irradiance than center modules in the same row, with a non-uniformity *((max-min)/(max+min)*100)* in the collector of 7-15%.





$$\text{Shading factor} = 1 - \frac{\sum Grear_{With\ Racking}}{\sum Grear_{Without\ Racking}}$$

Shading and Glint from Array Racking

When modeling the NIST array, we added in the largest elements of the racking structure. As we did not have design specifications, the three closest sizes of industry standard I-Beams were modeled (labeled above as "small", "medium", and "large"). Each size of I-Beam creates a similar glint and shading region across the rear face, and depending on where measurements are taken, they can vary by -0.5 to 3x from an average. Test points must be chosen carefully to fit the structure and match field data sampled locations.

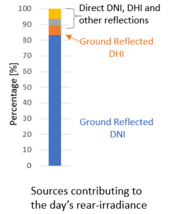
The beams contribute to a shading factor of 13.7%.

Degradation also varies across the row and across the collectors (5-up modules in landscape) themselves. Table 1 shows the relative degradation of the backsheet versus the front of the module as computed using Eq. 1. For the hour modeled, the top edge in the center row experience 75% more degradation than the middle of the center module of the array (highlighted with a red square), or 45% relatively more degradation than the 10% commonly assumed. Edge effects of the collector itself also represent a 20% increase in degradation for the top module in the collector relative to the center module.

	Rear Degradation Relative to Front [%]			
Sensor Location	Center Row, West Edge	Center Row, Center	Center Row, East Edge	South 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

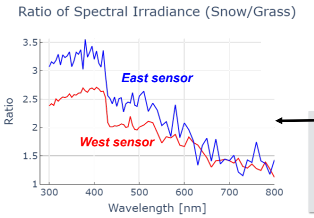
Investigating Albedo Effects on Degradation with NREL 75kW HSAT (Golden, CO)

A clear sky winter day was modeled (February 7th, 2021) For this day over 80% of the rear POA is ground reflected, that means the spectra has been modified by the albedo.



Sources contributing to the day's rear-irradiance

Using the same SRRL weather data for each model, a simulation was performed with snow and dry grass as the ground albedo. For 10 AM, we see how snow increases the UV wavelengths incident in the rear POA by 3x.



Likewise, the rear degradation (relative to the front) is much higher with snow, around 55-62% where the relative degradation with dry grass was modeled between 28.8 – 29.7%.

Rear Degradation Relative to Front

	West Edge	East Edge
Snow	62%	55%
Dry Grass	29%	30%

There are also sensor-placement effects; for 10 AM the East sensor is closer to the ground, perceiving more Snow-reflected light instead of more sky-contributed irradiance.

Integrated spectral simulations matched the IMT measurements <2 W/m² for this hour

Conclusion

Albedo has a large impact on rear irradiance and can greatly increase the rear UV-irradiance beyond the 10% assumption, and likewise with degradation. Rear-irradiance is further impacted by racking structures and array geometry. To properly validate field data, test points must be precisely recorded, and large racking structures will have to be included and coordinated within any simulation. More modeling is needed to determine degradation ratio sensitivity to all these factors.

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