ABSTRACT: Two experimental setups using ultraviolet (UV) light-emitting diodes (LEDs) for the purpose of accelerated photovoltaic (PV) module and material aging are built. The first setup consists of 8 small chambers, each equipped with one UV LED. Radiance, operation mode (pulsed or constant), duty cycle and frequency can be controlled. It is used to degrade glass-EVA-glass samples at room temperature (T). After more than 6500 hours, a loss of UV absorptance and to a lesser extent a reduced transmittance in the low-wavelength visible spectrum can be observed. The second setup is to be used inside a climatic chamber and consists of an aluminum plate, able to hold an array with up to 20 LEDs. The LEDs are water cooled and sealed with UV-transparent glass to protect them from high humidity. The radiance of the LEDs is individually adjusted to reach a homogeneous irradiance distribution at the target area. The plate can be used as a building block for larger arrays.

Keywords: degradation, LED, UV light

1 INTRODUCTION

Various environmental factors influence the degradation of PV modules mounted in the field. The most crucial are T, relative humidity (RH) and UV light [1]. The latter has been shown to degrade the polymeric materials used in PV modules, causing embrittlement, changes in transmissivity of the encapsulant and delamination [2].

Conventional setups with UV light sources use fluorescence tubes [3], mercury lamps [4] or xenon arc lamps with corresponding wavelength filters [2]. However, LEDs are gaining an increased market share in applications requiring light in the UV spectrum [5]. This trend is driven by big technological advancements and various advantages of LEDs compared to the conventional UV light sources. These advantages include a higher efficiency, a longer lifetime, more constant radiance and less heat generation [6].

Current IEC standards include UV light only as a UV preconditioning test, subjecting the module to at least 15 kWh/m² at (60 ± 5) °C without RH control [7]. There are no combined cycles defined in these standards, including elevated T, RH and UV light at the same time.

New combined cycles are being investigated for this purpose [8-10]. The goal is to duplicate failure and degradation modes observed in the field in a shorter amount of time, while not producing any others by using overly harsh parameters. The advantages of the combined tests include the possibility of using fewer modules and fewer parallel tests, reducing costs and time needed [10].

Thus, it is imperative to evaluate the option of using UV LEDs in PV module and component degradation. For this purpose, two experimental setups including these devices are built.

In this paper, the design of both setups is presented. Section 2 shows the design of a small chamber with eight UV LEDs. Furthermore, it presents the results of the degradation experiment of glass-EVA-glass samples in this setup, and the measurements of the LEDs’ degradation. Section 4 shows the design of a water-cooled UV LED array, able to be used inside a climatic chamber.

2 UV LED CHAMBER

2.1 Experimental setup

The first setup consists of 8 chambers, each equipped with a single LED as a light source. A custom driver [11] for every LED and the corresponding software enable their pulsed operation with control of radiance, frequency and duty cycle, or their constant operation with control of radiance, shown in Fig. 1.

Fig. 1: Electronic driver for UV LEDs

Two different types of LEDs are used: Four LED Engin LZ1-00UV00-0000 with a peak wavelength of 365 nm, and four Vishay Semiconductors VLMU3500-385-060 with a peak wavelength of 385 nm. Each is mounted on a heatsink and air-cooled by a fan.

6 × 6 cm big glass-EVA-glass samples are being degraded in the chambers. Their transmittance between 280 nm and 1200 nm is measured in regular intervals with a spectrophotometer.

The radiance of the LEDs is evaluated with an integrating sphere and a Hamamatsu S1226-8BQ silicon photodiode in the same intervals, enabling the analysis of the LEDs’ degradation over time. The input current to all LEDs is readjusted to keep their radiance constant over time.

The impact of two factors is analysed: the irradiance, controlled by varying the current input to the LEDs, and the frequency during pulsed operation.
The four 365 nm LEDs are operated at various currents. The highest irradiance on a sample is (190 ± 15) W/m². The other three are dimmed, achieving an irradiance of 75%, 50% and 25% of this value, respectively. The error is estimated. The largest source of uncertainty is the measurement with the photodiode.

Three of the four 385 nm LEDs are pulsed with a duty cycle of 50%. The peak irradiance on the sample is (162 ± 15) W/m². The frequencies are 1 Hz, 10 Hz and 100 Hz. The fourth LED is operated constantly, but dimmed to 50% of the peak irradiance of the other LEDs. Thus, the integrated radiance of those four LEDs is the same. Table I lists the parameters of all LEDs used in the experiment.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Operation mode</th>
<th>Frequency [Hz]</th>
<th>Peak power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>365</td>
<td>constant</td>
<td>n/a</td>
<td>100</td>
</tr>
<tr>
<td>365</td>
<td>constant</td>
<td>n/a</td>
<td>75</td>
</tr>
<tr>
<td>365</td>
<td>constant</td>
<td>n/a</td>
<td>50</td>
</tr>
<tr>
<td>365</td>
<td>constant</td>
<td>n/a</td>
<td>25</td>
</tr>
<tr>
<td>385</td>
<td>constant</td>
<td>n/a</td>
<td>50</td>
</tr>
<tr>
<td>385</td>
<td>pulsed</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>385</td>
<td>pulsed</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>385</td>
<td>pulsed</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table I: LED parameters

The LEDs degrade over time. To avoid using them at currents above their nominal current according to the datasheet, it is reduced by the same factor for all LEDs after 3900 hours of operation. The highest irradiance on the samples of the 365 nm LEDs used afterwards is (174 ± 15) W/m², the peak irradiance on the samples of the pulsed 385 nm LEDs is (149 ± 15) W/m².

2.2 EVA degradation

The experiment is ongoing for more than 6500 hours at room T. After this time, the measurements of the samples show two types of degradation, most pronounced at the highest used irradiance.

- The spectral transmittance in the UV-A spectrum of the light decreases, especially below the cutoff wavelength of approximately 370 nm, shown in Fig. 2.
- The transmittance in the visible spectrum decreases slightly in the early stages of degradation, most pronounced at low wavelengths, depicted in Fig. 3. However, it does not change after approximately 1000 hours of degradation.

Fig. 2: Increase of UV light transmittance

The largest loss of UV light absorbance can be observed under high intensities of light. The changes to the transmittance in the visible spectrum are too small to yield conclusive results about the influence of the irradiance.

Table II lists the incline of a linear regression of the transmittance between the first measurement after 168 hours, and the last measurement after 6589 hours \(i_t\). The samples taken are degraded under 365 nm light.

<table>
<thead>
<tr>
<th>Average irradiance ([W/m²])</th>
<th>(i_t) at 350 nm ([%/1000\ h])</th>
<th>(i_t) at 365 nm ([%/1000\ h])</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 ± 15</td>
<td>0.96</td>
<td>1.30</td>
</tr>
<tr>
<td>135 ± 15</td>
<td>0.45</td>
<td>0.69</td>
</tr>
<tr>
<td>90 ± 10</td>
<td>0.23</td>
<td>0.65</td>
</tr>
<tr>
<td>45 ± 10</td>
<td>0.31</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Table II: Change in transmittance in of the samples at two specific wavelengths

There are no changes in the spectral transmittance of EVA measurable after the degradation with 385 nm light. The experiment is ongoing.

2.3 LED degradation

The LEDs are degrading over time. Operating them under pulsed conditions at high frequencies (10 Hz, 100 Hz) do not change the degradation compared to constant operation. However, no degradation could be measured yet at the LED operated pulsing with a frequency of 1 Hz. The results are shown in Fig. 4.

Fig. 4: Degradation of the radiance of UV LEDs at room temperature

The degradation is very slow, demonstrating the long lifetime of LEDs compared to other UV light sources. This result emphasizes their applicability in PV module and component aging.

3 UV LED ARRAY

3.1 Irradiance calculation

The LEDs are approximated as nonperfect Lambertian emitters [12].
\[ E(r, \theta) = E_0(r) \cdot \cos^m \theta \] (1)

\( \theta \) is the viewing angle, \( E_0(r) \) the irradiance at distance \( r \) in front of the LED and \( m \) a parameter describing the radiance distribution.

\[ m = -\ln 2 \frac{\ln(\cos \frac{\theta_1}{2})}{\ln 2} \] (2)

\( \theta_{1/2} \) is a LED-specific parameter, describing the viewing angle at half irradiance. The irradiance at an arbitrary point \((x, y)\) of a flat surface at distance \( z \) from the LED, with an LED at the position \((x_0, y_0)\), is then:

\[ E(x, y, z) = \frac{l_0 \cdot z^{m+1}}{\left[(x-x_0)^2 + (y-y_0)^2 + z^2\right]^{(m+3)/2}} \] (3)

\[ l_0 = E_0(1 \text{ m}) \] (4)

To obtain the irradiance of an array of \( n \) LEDs, the irradiances from the single LED sources are summed up.

\[ E_{\text{total}}(x, y, z) = \sum_{i=1}^{n} E_i(x, y, z) \] (5)

3.2 Irradiance optimization

Operating all LEDs at their nominal current results in an inhomogeneous irradiance at the target area. It is strongest in front of the center of the array, and weaker in the corners. There are various possibilities to homogenize the irradiance:

- Optimizing the positions of the LEDs
- Adding optical components
- Dimming the central LEDs

The choice is made to optimize position and radiance of the LEDs. An iterative optimization method is devised \([13]\) and improved.

An array of optimization points (OPs) is inhomogeneously spread over the target area. Their positions depend on the placement of the LEDs on the array. Every LED is connected to a set of OPs closest to it. With this basic geometry in place, two steps for the optimization of the irradiance are repeated.

In the first step, the irradiance at all OPs is calculated according to equation (5). The average of those values, and the averages of the values for the OPs connected to each LED are calculated.

In the second step, the irradiances of the LEDs are changed individually. In the end, the obtained values are normalized to the highest used radiance. A flowchart of the method is shown in Fig. 5.

![Flowchart of the irradiance optimization method](image)

To obtain the ideal distance between the LEDs, the optimization is repeated, the irradiance over the entire target area calculated, and the results compared.

Fig. 6 shows the standard deviation and the difference between minimal and maximal irradiance during the first 50 steps of the iteration method. The target area is a 50 x 50 cm² square in a distance of 10 cm to the LED array.

![Convergence of the optimization method](image)

The LED array for this setup is a 9x9 checkerboard style array, using 40 LEDs with \( \theta_{1/2} = 55^\circ \). The result after 100 steps of the iteration is shown in Fig. 7. The blue bars indicate the radiance of the LEDs, relative to the maximum. The irradiance calculated is shown in Fig. 8. The standard deviation is 1.5%, the difference between minimum and maximum 9.8%.

![Array and optimized, normalized radiance in [%]](image)

These results can be further improved by using larger arrays. An 11x11 LED checkerboard style array results in a standard deviation of 0.5%, a difference between minimum and maximum of 2.7%, and a 30% higher irradiance. However, it uses 60 LEDs, 50% more than the 9x9 array.

3.3 Array design

Each LED is mounted on a custom designed PCB \([14]\), shown in Fig. 9. A single master controller can set the LED power individually, connected in a daisy-chain topology. A universal LED pattern is designed, able to fit various types of LEDs.

These PCBs are mounted on an aluminum plate. Channels in the back of the plate are used for water-
cooling. A plate of highly temperature resistant acrylic glass is used to seal these channels. A groove inside the aluminum plate filled with a rubber gasket, as well as a special isolating tape, placed between glass and aluminum plate, provide the necessary isolation to avoid water egress.

The front side is covered with a UV transparent glass. Because the array will be used inside a climatic chamber at elevated temperatures and humidity, a groove inside the aluminum plate filled with a gasket provide isolation against humidity ingress to the LEDs. The front side of the design is shown in Fig. 10.

A 26 × 33 cm² plate can hold up to 20 LEDs. It can be used as a building block to upscale the setup for larger areas. For a 50 × 50 cm² target area, 4 plates are used, with 10 LEDs on each plate.

Preliminary testing of the prototype provides a proof of concept for the drivers and the water cooling design. Further steps will characterize the array working in a climatic chamber at elevated temperatures and humidities, and the degradation of the LEDs in these conditions.

4 CONCLUSION

The UV LEDs have proven their long life-time and slow degradation at room T and RH. However, also polymeric materials only degrade slowly in those conditions. This emphasizes the need to apply UV light and other stress factors at the same time in accelerated aging and degradation testing.

The LED array design and calculations for the irradiance optimization have been presented. Preliminary tests show a proof of concept for the electronic drivers and the cooling system. Future work will include testing the array at elevated T and RH in the climatic chamber and analyzing the degradation of the radiance.

5 ACKNOWLEDGEMENT

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6 REFERENCES