Optical characterization of backsheets to improve the power of photovoltaic modules

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Abstract: On the photovoltaic module fabrication, the choice of one or other backsheet has a great importance in order to ensure its lifetime for 25 years or even for longer periods of time. It has the function of protect the solar cells, the encapsulant and the metallic contacts against ultraviolet radiation, water vapor and moistures. Besides, it has to provide a durable adhesion with the encapsulant, thermal and dimensional stability and electrical isolation. In the way to increase the efficiency of the photovoltaic solar modules and to reduce its price per Wp, the global reflectance of the backsheet takes importance. In this sense, a higher reflectance can allows to a better reuse of the incident sunlight. But that affirmation is not always true. An experimental analysis shows that there is another topic to take in account in order to choose the best backsheet: the angular dependence of the reflected light. Different backsheets with TEDLAR®, KYNAR® and PET layers from different suppliers have been analyzed. This study demonstrate than, for backsheets with similar global reflectance, the angular response of the backsheet is responsible for up to 0.7% of variation on the short circuit current of a photovoltaic (PV) module.

Keywords: Backsheet, PV module, reflectance, angular dependence, light trapping.


1 Introduction

Nowadays, the vast majority of crystalline silicon PV modules are formed by a transparent front side cover, which receives the sun light; some interconnected solar cells, which produces the electricity when the light shines on them; a backsheet, to protect the solar module and the encapsulating materials, and to provide electrical isolation. Solar cells are embedded in an encapsulant, mainly ethylene-vinil acetate (EVA) or silicone, which provides a high optical transparency over the solar spectrum, good adhesion, and excellent moisture and mechanical protection. Finally, the PV module has a connection box on its back side, and a frame, which confer stability and torsional stiffness.

When a ray of light falls to a PV module, it can be reflected, absorbed or transmitted in any of its components. McIntosh et al. and Jaus et al. exposed that, according to Fig. 1, incident ray
of lights can be absorbed in the glass (2), the encapsulant (4), the solar cell (5), and the backsheet (7). Besides, incident rays reflect from the air-glass (1), glass-encapsulant (3), encapsulant-solar cell (6), encapsulant-backsheet (8) interfaces and from the front side metallization of the solar cell. Mainly in the case of the backsheet, the reflection is often diffuse, leading to a reuse of some of the reflected light due to a total internal reflection at the glass-air interface [1,2]. Finally, depending on the thickness of the backsheet, some light can transmitted and escape from the PV module.

Fig. 1: Cross sectional diagram of a conventional PV module (to scale), and optical loss mechanisms [1].

Related to the backsheet, different colors can be chosen depending on the place where the PV module is going to be installed. In general, in order to make a better use of the light falling on them and due to its higher reflectance, the PV backsheet have a white color.

According to the layers that form the backsheet, the market offers three different possibilities:

- **Double fluoropolymer:** It has mainly the outer layers of TEDLAR® or KYNAR®, and a core layer of PET. The molecular structure of fluoropolymers is based on a chain of carbon atoms completely surrounded by fluorine atoms. Those ones are responsible of a better protection of the atoms chains presented on the layer [3]. Related to the price, those kinds of backsheets are the most expensive ones.
- **Single fluoropolymer:** A way to reduce the cost of the backsheet keeping a good behavior and durability is to reduce the number of fluoropolymer layers from two to one. In this case, the layer structure is formed mainly for TEDLAR® or KYNAR® on the air side, and PET and Primer or EVA layers on the inner one.
- **Non fluoropolymer:** It is made mainly by two PET and one Primer or EVA layers. It is the cheapest option. In the past it was not consider due to a possible degradation under UV exposure or hydrolysis over long time spans [4]. On the other hand, significant advances in polyester chemistry and production engineering have allowed the development of highly UV durable polyester films.

Attending to those possibilities, a study of the optical performance of different white backsheets from each type and its influence on the short circuit current of a PV module is going to be presented.
2 Reflectance components of a backsheet

A great percentage of the incident light on a white backsheet is globally reflected. That global reflectance has two components: specular and diffused. In order to reuse a large amount of the light which falls on the backsheet, the diffuse component takes relevance. In this sense, the angular dependence of the backsheet has a great importance on the percentage of the reflected light that can be reused for the solar cell.

![Cross section diagram of a conventional PV module.](image)

According to Fig. 2, for a ray of light which falls perpendicular to the PV module and taking in account the refractive index of the encapsulant, the glass and the air, the Snell’s law shows that the critical angle to achieve the total internal reflection is giving by:

\[
\theta = \arcsin \left[ \frac{n_{\text{air}}}{n_{\text{glass-EVA}}} \right].
\]  

(1)

For a glass with a refractive index of 1.5, the internal reflectance angle \( \theta \) at the glass-environment interface must be higher than 42\(^{\circ} \) to redirect a ray of light to a solar cell. For lower angles, most of the light will escape from the PV module and does not contribute to increase the current of the solar cells.

If \( d \) is the glass + encapsulant thicknesses, the length \( L \) traveled by the diffused light inside the module is:

\[
L = 2 \times d \times \tan(\theta).
\]

(2)

Besides, according to the Fresnel’s equations for the reflection and transmission of the light, the specular component of the reflected light takes more relevance if the incident light falls with a higher angle respect to the normal of the backsheet.

With those ideas in mind, taking as origin the point where the light falls on the white backsheet of a PV module, the reflected light has the following behavior:

1. According to Eq. 2 and as it is presented in Fig. 2, there is a first circle of light associated to the incident photons. Those ones will be reflected and escape from the PV module until a circle of radius \( L/2 \). Its intensity is the highest at the center (specular component), decreasing as it moves away.
2. Besides, due to the total internal reflection of a ray of light which strikes the interface between the glass and the air with an angle higher than 42°, the reflected light will fall again to the back side of the PV module (the solar cell or the backsheet), defining a new circle of radius $L$. The intensity of light decreases with increasing the distance from the center of the circle.

3. No light is expected between both circles.

Fig. 3 exposes this behavior on a PV module. A green laser has been used as a punctual source of light.

![Fig. 3: Enlarged photography of the light reflectance response on a PV module.](image)

The highest or lower intensity of the reflected light in each region depends on both the global reflectance and the angular dependence of the backsheet. Because of that, it has a great importance on the percentage of the reflected light that can be reused for the solar cell.

3 Experimental results

The optical performance of seven different TEDLAR®, KYNAR® and PET photovoltaic white backsheets from different suppliers is going to be studied. Their main features are shown in Table 1.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Structure</th>
<th>Total Thickness (µm)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PET/Al/PET/Primer</td>
<td>370</td>
<td>Al extra moisture barrier</td>
</tr>
<tr>
<td>B</td>
<td>PET/PET/Primer-1</td>
<td>365</td>
<td>Extra PET thickness</td>
</tr>
<tr>
<td>C</td>
<td>PET/PET/Primer-2</td>
<td>300</td>
<td>PET films</td>
</tr>
<tr>
<td>D</td>
<td>PET/PET/Primer-3</td>
<td>275</td>
<td>PET films</td>
</tr>
<tr>
<td>E</td>
<td>PVDF/PET/Primer</td>
<td>310</td>
<td>KYNAR/Primer</td>
</tr>
<tr>
<td>F</td>
<td>PVDF/PET/PVDF</td>
<td>315</td>
<td>KYNAR films</td>
</tr>
<tr>
<td>G</td>
<td>PVF/PET/PVF</td>
<td>325</td>
<td>TEDLAR films</td>
</tr>
</tbody>
</table>

**Table 1**: Main characteristics of the backsheets studied.
The objective is to check and compare the optical characteristics of double fluoropolymer, single fluoropolymer and non fluoropolymer backsheets, taking into account its influence in the photocurrent of a PV solar module.

Optical measurements have been carried out using a spectrophotometer SpecWin Light CAS 140CT and a 150 mm integrating sphere from Instruments Systems. The characterization of the PV solar mini modules made with those backsheets has been done with a class A solar simulator from Abet Technologies.

High efficiency monocrystalline silicon solar cells with similar electrical parameters have been used to study the impact of the backsheet reflectance on the short circuit current ($J_{sc}$). PV mini modules have been made up with one solar cell. The same low iron PV glass and encapsulant have been always utilized. Three measurements have been done in each case. The average short circuit currents and its variation against the average reflectance between 400 and 1100 nm are presented in Fig. 4.

![Fig. 4: Relationship between the average global reflectance of the backsheet and the short circuit current of the PV mini module.](image)

According to those results, and regardless of the use of fluoropolymer or no fluoropolymer based backsheets, in general the relationship between the average reflectance and the short circuit current is almost lineal. Because of that, backsheets with higher reflectances are necessary to improve the power of a PV module. A similar tendency has been shown by other researches [5]. With those results in mind, comparing the analyzed backsheets with the highest and the lowest global reflectance, an increase of 0.75% absolute on the power can be achieved. Extrapolating it to a standard PV module, the power shifts from 255.00 W to 256.93 W.

But on the other hand, in our study it has been found one backsheet where that behavior has not been so. In this sense, the module with the backsheet with the highest global reflectance (the C one) has one of the lowest short circuit currents. The variation measured on the short circuit current is up to 0.7%. Assuming no changes on the open circuit voltage and on the fill factor of a PV module, that variation supposes a power increases from 255.00 W to 256.75 W.

To give an explanation of that behavior, a study of the angular dependence of the light reflected on the backsheet is presented below.
3.1 Angular dependence of different backsheets

Two PET based backsheets with similar average global reflectances but with a notable difference on the short circuit current measured on test mini modules have been selected for this study: the C and the D ones.

Based on Thorlabs’ optics components, an angular measurement set up has been performed to determine the angular dependence of the light reflected on those backsheets. In order to analyze the specular reflectance, the backsheets have been rotated 5° respect to the ray of light. Fig. 5 shows a schema of the set up used.

![Set up used to measure the angular dependence of the backsheets.](image)

The laser has been positioned at 180°. Then, the specular reflectance of the backsheet is found at 170°. To obtain the angular dependence, both the laser and the backsheets have been kept in constant positions. The spectrometer has been turned from 170° to 90° using a Thorlab’s NanoRotator 360° rotation stage and the APT precision motion controller.

A red laser with emissions at 633 nm has been selected for this study. The reasons for choosing this laser are that the backsheet has a high reflectance at 633 nm, and the external quantum efficiency of a standard crystalline silicon solar cell has maximum values close to that wavelength. Fig. 6 shows the angular dependence on backsheets C and D.

![Angular dependence on two PET based backsheets.](image)

According to Eq. 1, the arrow indicates the percentage of reflected photons that can be reused.

In accordance with Fig. 6, there is a clear difference between the backsheet C and D on their angular responses. For backsheet C, the specular component has a great importance against the diffused one. On the other hand, for backsheet D the diffused reflectance has a higher magnitude. Because of that, it is conceivable that the diffuse component of the reflected light is higher for all
wavelengths on backsheet D. The percentage of reflected photons that can be reused is 37% and 48% for backsheets C and D respectively. This difference justifies the variation found on the short circuit current of the analyzed PV mini modules.

4 Summary

A study of the optical features and its relationship with the short circuit current of PV mini modules done with four non fluoropolymer (three different PET/PET/Primer and one PET/Al/PET/Primer), one single fluoropolymer (KYNAR®/PET/Primer) and two double fluoropolymer (KYNAR®/PET/KYNAR® and TEDLAR®/PET/TEDLAR®) based backsheets has been presented.

It has been shown that in general and regardless of the use of fluoropolymer or no fluoropolymer based backsheets, the relationship between the reflectance and the short circuit current of a PV mini module is almost lineal. But it has been found one PET based backsheet that does not follow this trend. To gives an explanation of that behavior, a characterization of the angular dependence of the reflected light demonstrated that despite having a high reflectivity, if the value of the specular component respect to the diffused reflectance increases, the current of the PV module will decreases. Because of that, in order to have a better correlation between the backsheet used and the short circuit current expected on a PV module, it is important to consider not only the global reflectance of the backsheets, but their angular dependence of the reflected light.

In our study, the highest currents have been obtained on the PV modules with KYNAR® and PET based backsheets. Comparing the backsheets with the highest and the lowest global reflectance, a variation of 0.75% on the short circuit current has been achieved. Besides, taking in account the average reflectivity of the backsheets, the angular response of the reflected light is responsible of a difference up to 0.7% on the short circuit current. That variation is equivalent to an increase of 1.75W in a PV module of 255 W.

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