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The importance of optical characterization of PV backsheets in improving solar module power

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ABSTRACT

With the objectives of reducing cell-to-module losses, improving module efficiency and reducing the price per watt, increasing importance is being placed on the optical properties of backsheets. It is assumed that a higher reflectance backsheet allows a better reuse of incident sunlight. However, this statement is not always true: another factor must be taken in account, namely the angular dependence of the reflected light. In this regard, backsheets with a high specular component deviate from the ideal Lambertian reflectance, resulting in a minor increase in module current. As a result, differences can be found in module power because of the use of backsheets with similar global reflectance but different angular components of reflected light. A total of 33 industrial backsheets with Tedlar, Kynar, EVA and PET layers from different suppliers were analysed. A comparison of backsheets with low and high global reflectances revealed that the power variation in a standard PV module reaches 0.54% abs. In the same vein, and for backsheets with similar global reflectances, it was experimentally found that the angular response of the reflected light was responsible for a power difference of 0.22% abs. in a standard module.

Introduction

PV backsheets play a very important role in ensuring a solar module lifetime of 25 years or even longer. They have the function of protecting the solar cells, the metallic contacts and the encapsulant against ultraviolet radiation, as well as against the penetration of water vapour and moisture from the atmosphere. Moreover, and with regard to module efficiency, the global reflectance is a significant factor in reducing cell-to-module losses and improving module efficiency.

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From an optical point of view, a ray of light which falls on a PV module can be reflected, absorbed or transmitted by any of its components. McIntosh et al. [1] and Jaus et al. [2] demonstrated that, as shown in Fig. 1, incident rays of light can be absorbed by the glass (2), the encapsulant (4), the solar cell (5) and the backsheet (7). Additionally, incident rays reflect from the air–glass (1), glass–encapsulant (3), encapsulant–solar cell (6) and encapsulant–backsheet (8) interfaces and from the front-side metallization of the solar cell. The reflection is often diffuse, particularly in the case of the backsheet, leading to a reuse of some of the reflected light because of a total internal reflection at the glass–air interface. Finally, depending on the thickness and the composition of the backsheet layers, some of the incident light can be absorbed by and transmitted from the PV module. In either case the light will not contribute to an improvement in the current of the solar cells present in the PV module.

Backsheets can be transparent or have different colours, depending on the location where the PV module will be installed. In general, the backsheet is white because of the higher reflectance and to make better use of the light falling on the module.

With regard to the layers that form the backsheet, the three main options offered on the market are:

- **Double fluoropolymer**: This consists mainly of outer layers of Tedlar polyvinyl fluoride (PVF) films, or of Kynar polyvinylidene fluoride (PVDF) films, and a core layer of polyethylene terephthalate (PET). The molecular structure of fluoropolymers is based on a chain of carbon atoms completely surrounded by fluorine atoms, which are responsible for a better protection of the atom chains present on the layer [3]. In terms of price, these kinds of backsheet are the most expensive.

- **Single fluoropolymer**: One way of reducing the cost of the backsheet while maintaining satisfactory behaviour and durability is to reduce the number of fluoropolymer layers from two to one. In this case, the layer structure is formed mainly with

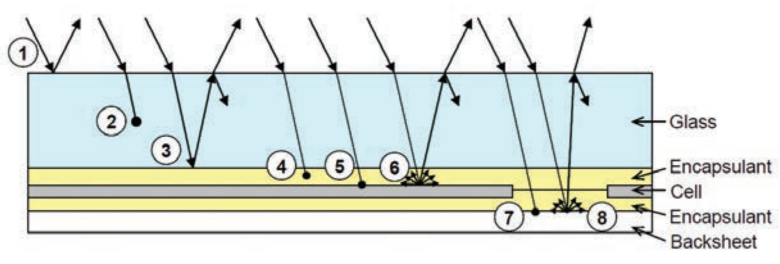

Figure 1. Cross-sectional diagram of a conventional PV module (to scale), and optical loss mechanisms [1].

Tedlar or Kynar on the air side, and with PET and primer or EVA layers on the inner side.

- **Non-fluoropolymer**: This consists of two PET and one primer or EVA layers, and is the cheapest option. In the past it was not considered because of the possible degradation under UV exposure or hydrolysis over long periods of time [4]. However, significant advances in polyester chemistry and production engineering have led to the development of highly UV-durable polyester films.

With these different possibilities in mind, a study was carried out of the optical performance of various white backsheets of each type and the influence on the short-circuit current (I_{sc}) of a PV module; the results are presented in this paper.

It is generally accepted that the short-circuit current and power of a PV module varies proportionally with the global reflectance of the backsheet [5]. In this paper it will be demonstrated that this statement is not always true: another parameter needs to be taken into account, namely the angular response of the light reflected by the backsheet.

Reflectance components of a PV backsheet

A large percentage of the incident light on a white backsheet is globally reflected. That global reflectance has two components: specular and diffuse. In order to reuse a large amount of the light which falls on the backsheet, the diffuse component is more relevant. In this respect, the percentage of the incident light that can be reused by the solar cell depends to a significant extent on the angular dependence of the light reflected in the backsheet.

According to Fig. 2, for a ray of light which falls perpendicularly on the PV module – and taking into account the refractive indices n of the encapsulant, glass and air – Snell's law shows that the critical angle θ for achieving a total internal reflection (TIR) is given by:

$$\theta = \arcsin\left[n_{air} / n_{glass\text{–}EVA}\right] \qquad (1)$$

For glass and encapsulant with a refractive index of 1.5, the internal reflectance angle θ at the glass–environment interface must be greater than 42° in order to redirect a ray of light to a solar cell. For smaller angles, most of the light escapes from the PV module and does not contribute to an increase in the current of the solar cells.

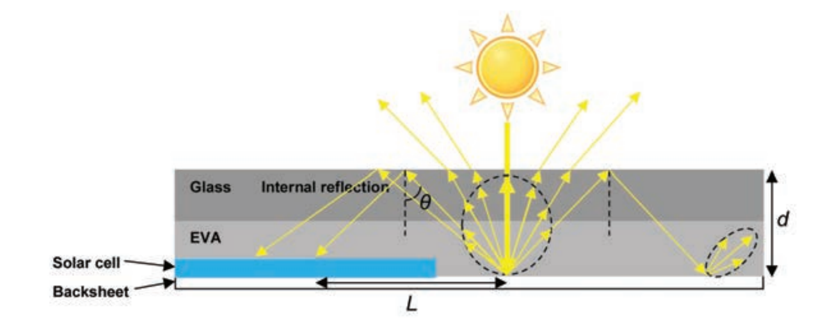

Figure 2. Cross section of a conventional PV module.

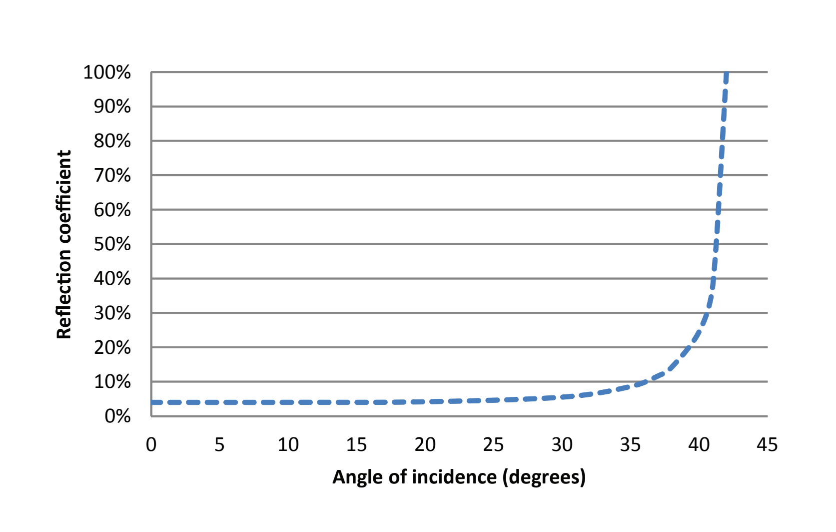

Figure 3. Reflection coefficient as a function of the angle of incidence for a non-polarized ray of light at the glass–air interface.

If d is the combined glass+encapsulant thickness, the length L travelled by the diffused light inside the module is:

$$L = 2 \times d \times \tan\theta \qquad (2)$$

Fig. 3 shows the percentage of light that is internally reflected at the glass–air interface for a ray of light which strikes at a given angle of incidence with respect to the normal of the glass. The percentages have been calculated using Fresnel equations [6], and assuming no polarization of the light reflected at the backsheet.

With those ideas in mind, and if the origin is taken to be the point where the beam spot falls on the white backsheet of a PV module, the reflected light has the following behaviour:

1. According to Equation 2, and as presented in Fig. 2, there is a first circle of light of radius $L/2$ associated with the incident photons that will be reflected and escape from the PV module. The intensity of the circle is highest at the centre (specular component), and decreases with increasing distance from the centre.
2. In addition, because of the total internal reflection of a ray of light striking the interface between the glass and the air at an angle greater than 42°, the reflected light will again fall on 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 distance from the centre of the circle.
3. No light is expected between the two circles, with the exception of Fresnel reflections of light for angles below the critical one, as shown in Fig. 3.

Fig. 4 reveals the above behaviour of a PV module; a green laser was used as a punctual source of light because of the human eye's higher sensitivity to this colour.

The higher or lower intensity of reflected light in each region depends on both the global reflectance and the angular dependence of the light reflected at the backsheet. As a consequence, this significantly affects the percentage of reflected light that can be reused for the solar cell in a PV module.

Reflectance measurements

In order to increase the efficiency of a PV module, the reflectance $R(\lambda)$ of a backsheet is of relevance. In this respect, the optical performance of 33 different backsheets with double, single and non-fluoropolymer layers was analysed. The global reflectance was measured using a SpecWin Light CAS 140CT spectrophotometer and an Instrument Systems 150mm integrating sphere. Equation 3 was used to calculate the effective reflectance R_{eff} between 400 and 1100nm under an AM1.5G solar spectrum; this is used to compare the backsheets and to calculate the influence of reflectance on current variation in a PV module.

$$R_{eff} = \frac{\int R(\lambda) AM\,1.5G(\lambda) d\lambda}{\int AM\,1.5G(\lambda) d\lambda} \quad (3)$$

Fig. 5 shows the effective global reflectance under an AM1.5G solar spectrum as a function of the cell-side layer of the backsheet. There is a large variation in effective reflectance, mainly depending on the type of backsheet cell-side layer; in general, white EVA seems to be the best choice. Furthermore, for backsheets with the same layers, large differences in measured global reflectances are also observed, implying that the backsheet fabrication process has a large influence on the final reflectance.

It is clear that the backsheet global reflectance is related to the short-circuit current of the PV module: higher global reflectances usually lead to higher short-circuit currents [5]. On the other hand, and as demonstrated by Equation 1, if the specular component is significant, most of the reflected light will escape from the PV module and will not contribute to increasing the current of the solar cells. For this reason, besides global reflectance another aspect needs to be considered: the angular response of the light reflected by the backsheet.

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Angular measurements

As discussed in the previous section, in order to reuse a high percentage of the incident light and to increase the current of a PV module, it is important to reduce the specular contribution and to increase the diffused component of

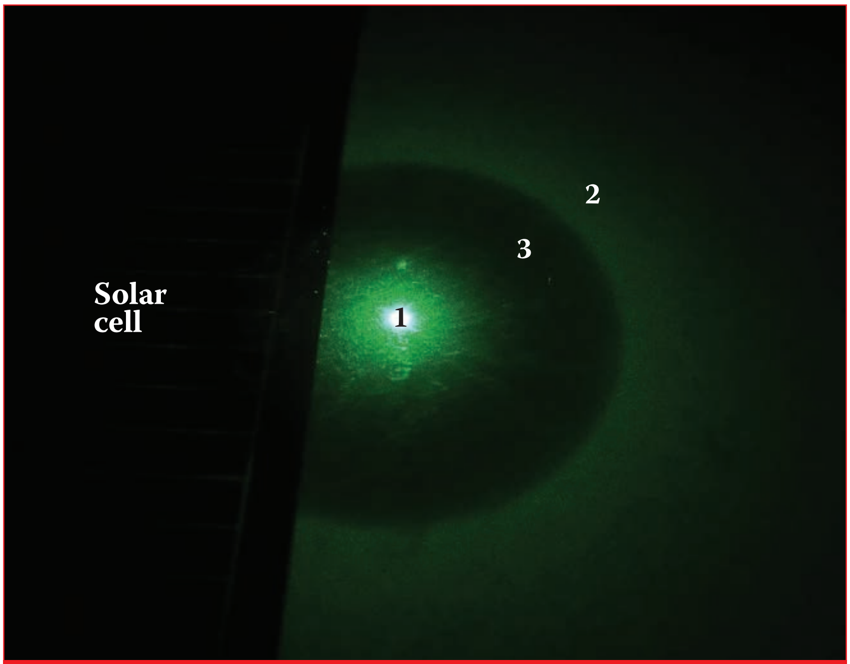

Figure 4. Enlarged photography of the light-reflectance response of a PV module.

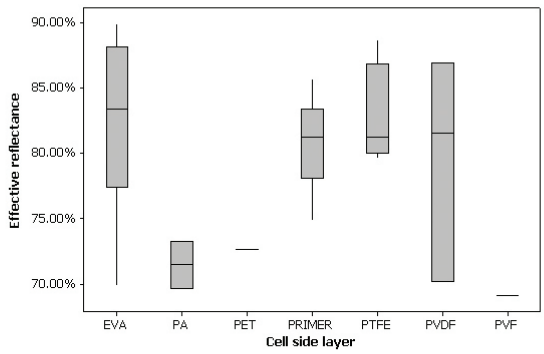

Figure 5. Effective global reflectance of the backsheets analysed. (Cell-side layers: EVA – ethylene vinyl acetate; PA – polyamide; PET – polyethylene terephthalate; PTFE – polytetrafluoroethylene; PVDF – polyvinylidene fluoride; PVF – polyvinyl fluoride.)

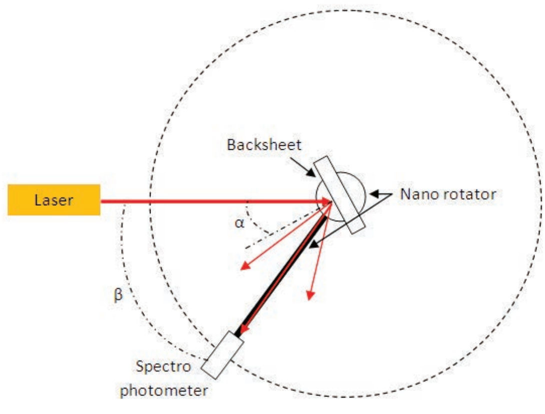

Figure 6. Set-up used to measure the angular dependence of the backsheets. The laser is placed in a fixed position, and the backsheet is put on a rotating base. The base can be rotated from α = 0 to 90°, where α is the angle between the laser beam and the perpendicular to the backsheet; this angle is kept fixed during a measurement. β is the angle between the laser beam and the spectrophotometer, and can vary from 0 to 360°.

the light reflected by a backsheet. In this regard, an ideal backsheet exhibits a Lambertian reflectance. (Lambertian reflectance is the property that defines an ideal diffusely reflecting surface.)

Based on optics components from Thorlabs, an angular measurement set-up (Fig. 6) was used to determine the angular dependence of the light reflected by the backsheets. To measure the angular dependence, both the laser and the backsheet were kept in a constant position. The spectrometer was turned using a Thorlabs NanoRotator 360° rotation stage and an APT precision motion controller. The angular measurement cannot be performed at angles between ±5° respective to the laser location because of the superimposition of the laser beam on the spectrophotometer.

A JDS Uniphase red laser with emissions at 633nm was selected for this study. As well as its stability, the reasons for choosing this laser were that the backsheet has a high reflectance at 633nm, and the maximum value of the external quantum efficiency of a standard crystalline silicon solar cell occurs near that wavelength.

On the basis of average global reflectance and layer structure, different backsheets with similar global reflectance were chosen for this study. In addition, various laser beam angles of incidence with the backsheet were selected: α = 5°, 40°, 60° and 70±2° (low-gloss to high-gloss regions respectively). Represented values are relative to the maximum reflectance measured for an aluminium foil.

The analysed backsheets can be split into three groups, depending on the level of specular reflection: A = high, B = medium and C = low. Fig. 7 depicts the angular response of representative backsheets with these characteristics; a photograph of the reflected light is shown on the right in each case.

According to Fig. 7(a), backsheets from group A have a notable specular component, which increases slightly with the incident angle of the light. As presented in Fig. 7(b), the specular peak of a backsheet from group B has a smaller intensity and is wider compared with the angular response of

PV Modules

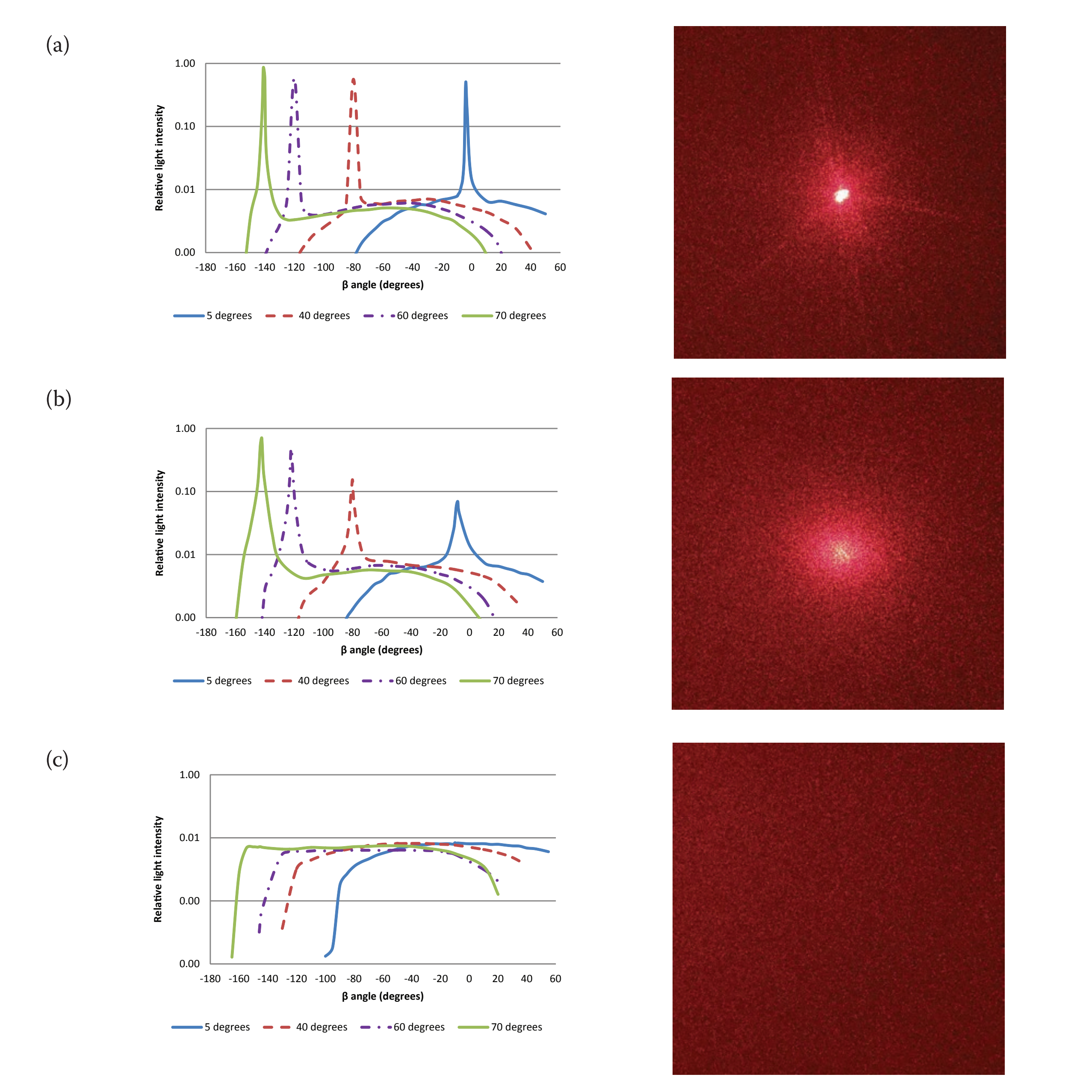

Figure 7. Angular distribution profiles for a backsheet with (a) high specular reflection (group A); (b) medium specular reflection (group B), and (c) low specular reflection (group C). The photograph on the right in each case shows the reflected light for an incident angle of 5°.

a backsheet from group A; moreover, the diffuse component has a higher relevance. When the incident angle of the light increases, the specular peak increases, whereas the diffuse portion decreases. Backsheets from group C have a Lambertian distribution for any incident angle, as seen in Fig. 7(c). Because of this, no specular peak is observed, and the reflected light is notably diffuse. Backsheets with EVA and fluoropolymer cell-side layers dominate in this group.

For a quasi-normal incidence of light (α = 5°), the cumulative reflectance of a representative backsheet from each group was calculated by integrating the measured light over the 2π solid angle; the trends achieved are shown in Fig. 8, along with the cumulative reflectance of an ideal Lambertian reflector [7].

Table 1 shows the expected percentage of light that is subjected to TIR in a PV module for each of the backsheet groups (taking into account the Fresnel reflections and the fact that TIR occurs for a ray of light reflected by the backsheets at angles greater than 42° with respect to the normal).

According to Table 1, the highest expected percentage of reflected light that is subjected to TIR is 52±2%. This value obtained experimentally is close to 56%, which corresponds to the theoretical value estimated by McIntosh et al. [8] for a Lambertian reflector embedded in EVA and glass. For backsheets with similar analysed global reflectances, there is significant variation in the percentages of light that are subjected to TIR. Comparing the backsheet having the highest specular component with that having the lowest one, the difference is almost 9% abs.

Moreover, and without considering multiple reflections, the total incident light on a backsheet that can be reused in a PV module depends on the backsheet's global reflectance. If both the global reflectance effect and the angular dependence of the light reflected by the backsheet are taken into account, the percentage of reflected light that can be reused is obtained using Equation 4:

$$\text{Reused light (\%)} = R_{\text{eff}} \int_0^{90} RC(\alpha)CR(\alpha)\text{d}\alpha \quad (4)$$

where R_{eff} is the effective reflectance (see Equation 3), $RC(\alpha)$ is the reflection coefficient for a glass to air interface, and $CR(\alpha)$ is the percentage of light reflected at the backsheet at an angle α.

The average global reflectivity of the high-reflectance backsheets utilized in this study is 86±2%. Consequently, and using Equation 4, the incident light on the backsheets that can be reused changes from 37.8±4% to 44.7±4%.

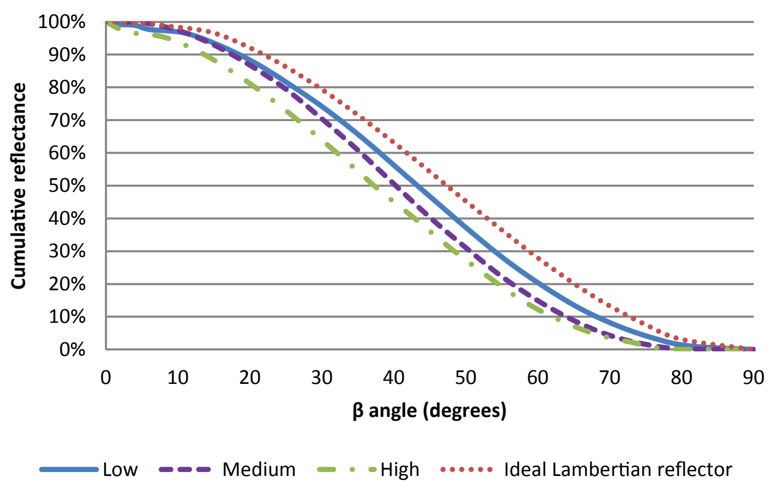

Figure 8. Cumulative reflectance of the selected backsheets with different specular components for a quasi-normal light incidence. An ideal Lambertian reflector is also shown.

Group	Specular component	Expected reflected light that is subjected to TIR
A	High	43±2%
B	Medium	47±2%
C	Low	52±2%

Table 1. Reflected light on the backsheet that can be reused.

The variation in the number of incident photons (N_{gain}) on the solar cell in a PV module is proportional to the incident photon flux (Φ), the spacing area between the solar cells and the light reflected on the backsheet that can be reused:

$$N_{\text{gain}} = \Phi \times \text{Spacing area} \times \text{Reused light} \quad (5)$$

The short-circuit current of a solar cell is proportional to the incident radiation up to extremely high light intensities, because of the incidence of a larger number of photons on the cell's active area. Further, a modification of the light intensity has an impact on the open-circuit voltage, which changes logarithmically, as well as on the fill factor, because of variations in the cell's internal resistance [9]. Both effects have an impact on the power of the solar cell. Because of the small variation in light concentration due to the effect of the backsheet, both open-circuit voltage and fill factor can be assumed to be constant.

The short-circuit current density (J_{sc}) can be calculated from the equation:

$$J_{\text{sc}} = q \int \Phi_{\text{mod}}(\lambda).EQE(\lambda)\text{d}\lambda \quad (6)$$

where q is the electron charge, Φ_{mod} is the photon flux taking into account the effect of the photons reflected on the backsheet, and EQE is the external quantum efficiency of the solar cell.

Fig. 9 shows the variation expected in short-circuit current per millimetre of distance between the cells in the case where the solar cell quantum efficiency is kept constant, and only the effect of the backsheet is considered. A low-reflectance backsheet, with a global reflectance of 73±2%, has also been included.

On the assumption of no change in open-circuit voltage and fill factor, according to Fig. 9 a backsheet with a low specular component yields a power improvement of 0.10% abs. per millimetre of separation between the cells over a backsheet with a high specular component. The standard separation between cells in a PV module is 2mm: in this case the theoretical power variation expected between PV modules processed using backsheets having similar global reflectances, but one having a low specular component and the other a high one, is 0.20% abs.

In a similar way, if backsheets with low and high global reflectances are compared, the power variation is 0.18% per millimetre: for a standard PV module with a separation between cells of 2mm, the expected power variation is thus 0.36% abs.

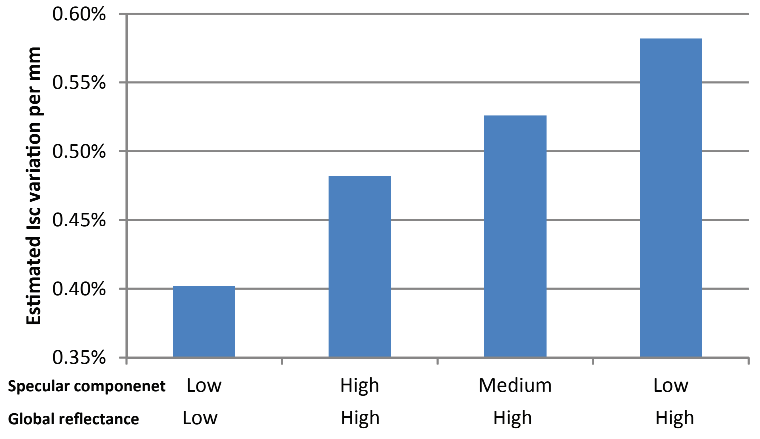

Figure 9. Estimated I_{sc} variation per millimetre of separation between cells for backsheets with different global reflectances and specular components.

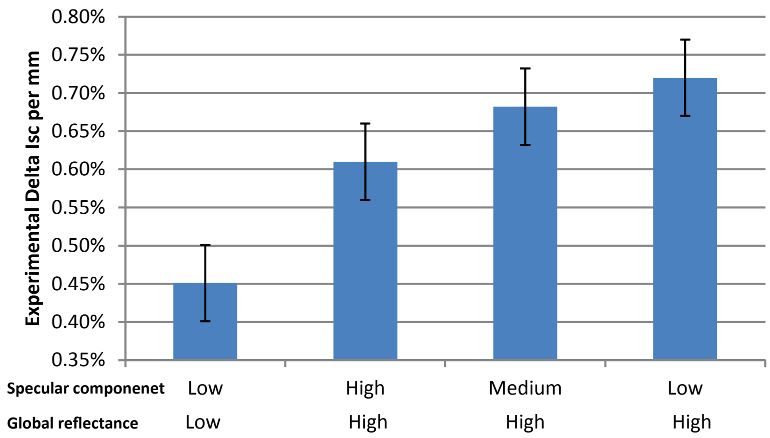

Figure 10. Experimental I_{sc} variation per millimetre of distance between cells.

Experimental study

High-efficiency, 156mm × 156mm × 0.18mm, multicrystalline silicon solar cells with similar electrical parameters were used to study the impact of backsheet optical performance on the short-circuit current of PV mini-modules. PV mini-modules were made up using one solar cell, with the same low-iron PV glass and encapsulant being utilized in each.

Three mini-modules were fabricated for each study group; their electrical characterization was performed under standard test conditions (STC) with an Abet Technologies class A solar simulator. The characterization was carried out using two different black masks: one with the same area as the solar cell, and the second with a separation of 5±0.3mm between the solar cell and the mask edges. Thus, the difference (as a result of the use of one or the other mask) in measured short-circuit current is due to the backsheet effect. At least three measurements were taken in each case.

Fig. 10 shows the average variation in short-circuit current per millimetre of backsheet, along with the standard deviations. It was assumed that the current variation is proportional to the separation between the cells [10].

The experimentally determined increment in short-circuit current with distance between cells is larger than the estimated value: this may be due to multiple internal reflections of light in the PV module, which have not been taken into account in the theoretical model. The effect is greater in backsheets with a higher global reflectance.

When only high-reflectance backsheets are used, and mini-modules processed with the highest and lowest specular components are compared, the average variation in current is in the range of 0.11% abs. per millimetre of separation between the cells. The experimental power variation in a PV module with cells spaced 2mm is therefore 0.22% abs. In other words, for backsheets with similar global reflectances, the angular response of the reflected light is responsible for a power variation of 0.22% abs. If a comparison is made between backsheets with high and low reflectances, the power variation works out to be 0.27% abs. per millimetre of distance between the cells: for a standard module, this implies a power variation of 0.54% abs.

> "For backsheets with similar global reflectances, the angular response of the reflected light is responsible for a power variation of 0.22% abs."

These results were used to calculate the efficiency variation in a standard industrial PV module with a separation of 2mm between cells. Comparing backsheets with high reflectances, but one having a high specular component and the second a low one, the efficiency increase of the latter is 0.22% rel. Moreover, if backsheets with different global reflectances are compared, the efficiency variation increases to 0.54% rel. in favour of the PV module processed with a high-reflectance backsheet.

Economic analysis

The impact of the optical behaviour of backsheets on the cost variations of a PV module was estimated from the results of the experiments; for this analysis the price of all the backsheets was considered to be the same. As a starting point, a PV module with 60 multicrystalline silicon solar cells and a power of 250W measured under STC was considered. The reference module price was $0.64/Wp [11].

When backsheets with similar global reflectances are considered, 0.14¢/Wp can be saved by reducing the specular component of the reflected light. This equates to an annual saving of $84 thousand per year for a 60MW manufacturing plant. However, a reduction of 0.34¢/Wp can be obtained by using a high-reflectance backsheet rather than a low-reflectance one, equating to an annual saving of around $206 thousand for a 60MW manufacturing plant.

Besides the module efficiency improvements, these results demonstrate the importance of backsheets in potentially reducing price per Wp, resulting in cost savings at an industrial plant.

Conclusions

The results of a study of backsheet optical properties and their influence on PV module efficiency, cell-to-module losses and price per watt have been presented. It is usually assumed that the reflection from the backsheet is approximately Lambertian, but this is not always the case. It was demonstrated that, as well as global reflectance, the angular response of the light reflected in the backsheet has a significant influence on the short-circuit current of a PV module.

A total of 33 backsheets formed of fluoropolymer and/or non-fluoropolymers layers was analysed. In spite of the variation found between different backsheets, white EVA films in general demonstrate the highest global reflectance, while backsheets with white EVA and fluoropolymeric layers yield the best angular response.

When backsheets with similar global reflectances are considered, theoretical studies indicate a power increase of 0.10% per millimetre of separation between cells in the PV module as a result of using a backsheet having a low specular component compared with a backsheet having a high specular component. Moreover, the difference is 0.18%/mm if a high-reflectance backsheet is used instead of a low-reflectance one. An experimental study determined those differences to be 0.11%/mm and 0.27%/mm respectively. Variations between theoretical and experimental study results may be due to the presence of multiple internal reflections of the light reflected in the backsheet.

"An improvement in efficiency of 0.22% rel. can be achieved in a standard PV module with the use of a backsheet having a low specular reflectance"

The efficiency of a PV module is influenced by the backsheet. In this respect, and for backsheets with similar global reflectances, an improvement in efficiency of 0.22% rel. can be achieved in a standard PV module with the use of a backsheet having a low specular reflectance compared with another having a high specular component. The efficiency improvement rises to 0.54% rel. if a backsheet with a high global reflectance is used rather than one with a low reflectance.

If the price of the backsheet is assumed constant, the use of one with a low specular component yields a reduction of 0.14¢/Wp compared with another having a high specular reflectance. If backsheets with high and low global reflectances are compared, the variation in the price per Wp is 0.34¢. These values represent, respectively, a saving of around $84 thousand/year and $206 thousand/year for a 60MW manufacturing plant.

Acknowledgements

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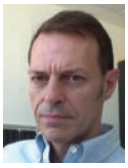
About the Authors

Salvador Ponce-Alcántara has a master's in electronic engineering from the University of Granada, and received his Ph.D. from the Solar Cell Institute of the Polytechnic University of Madrid (UPM). Since 2007 he has worked in the R&D departments of different companies (Pevafersa, Isofotón) on the optimization of fabrication process steps for high-efficiency crystalline silicon solar cells and PV modules. He joined the Valencia Nanophotonics Technology Center (NTC) at UPV in 2011 as head of the PV module section.

Alberto A. Vivas Arangú has a diploma degree in electronics engineering from the Polytechnic University of Antonio José de Sucre in Venezuela. He received a master's in system integration and corporative networks from the Polytechnic University of Valencia (UPV), Spain. In 2014 he participated in an R&D project developed at the Valencia Nanophotonics Technology Center at UPV that concerned an optical study of photovoltaic backsheets in order to improve the power of solar modules.



Guillermo Sánchez Plaza is a co-founder of the Valencia Nanophotonics Technology Center at UPV, where he is currently the Director of Technology. He began research in the PV area in 2009 and has extensive experience in nanomanufacturing processes for optoelectronic devices, on both industrial and laboratory scales.

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