# LIGHT TRAPPING FILM FOR BIFACIAL APPLICATIONS

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ABSTRACT: DSM's light trapping film (LTF) is applied to bifacial modules to improve the energy yield for vertical, east/west facing applications. The LTF increases the current both at test conditions (STC) and under high albedo with about 4% compared to planar solar glass, due to the better anti-reflection (AR) and light trapping properties. Without LTF, the current drop due to reflection at the air/glass interface increases from 4% to 45% for incident angles between 0 and 85°, With LTF it remains between 1 and 4%, coupling almost all light at all angles into the module. Optical, thermal and electrical modelling together with time resolved meteorological data results in time resolved output power. This shows that for east/west facing vertical modules 60% of the calculated energy output is generated at incidence angle >55°, versus 20% for equator-facing modules. Applying the annual energy yield (AEY) model to bifacial modules in vertical applications, we show that there is >6% gain in AEY by the addition of LTF. In general, as LTF is most effective for light incident at higher angles, systems that have a large contribution from either (or both) diffuse or ground reflected light will benefit the most from addition of LTF.
Keywords: Bifacial; Light Trapping; Energy Rating

## 1 INTRODUCTION

There is an increased attention for vertical applications of photovoltaic modules, e.g. in noise barriers and desert applications. When oriented with one side facing east and one facing west a double-peak power generation profile results. This complements equator-facing modules and can result in a better daily energy generation distribution. Under circumstances with suitable albedo vertical bifacial modules can outperform conventionally orientated equator-facing modules. However, when applied vertically, a large fraction of the sunlight hits the panels at unfavourably high angles. To further improve the performance of vertically installed modules, we have investigated the application of a light trapping film (LTF), on bifacial glass-glass modules.

DSM's LTF, an innovative new module material, is a durable polymeric layer that is applied on the outside of the module glass. LTF comprises a regular texture based on single apex corner cubes, see Figure 1. The film has both an AR-function and it simultaneously improves the light trapping at higher angles.

In this contribution, we have applied DSM's LTF to high efficiency, low cost bifacial n-Pasha cell and module technology [1]. n-Pasha cells are high-efficiency n-type cells and are bifacial by nature. Specifically, the focus is on improving the light trapping of bifacial n-type c-Si glass-glass modules, which were measured under laboratory conditions at different angles, by applying textured LTF on the front side and on both sides. Furthermore, the impact on annual energy yield (AEY) for east/west facing, vertical applications was assessed and quantified by energy yield modelling for temperate and desert locations.

## 2 EXPERIMENTAL SET-UP

### 2.1 IV-measurements

For the experiments 2×2-cell mini modules have been used. The cells with dimensions of 156 × 156 $mm^2$ (semi-square) were series connected and laminated between

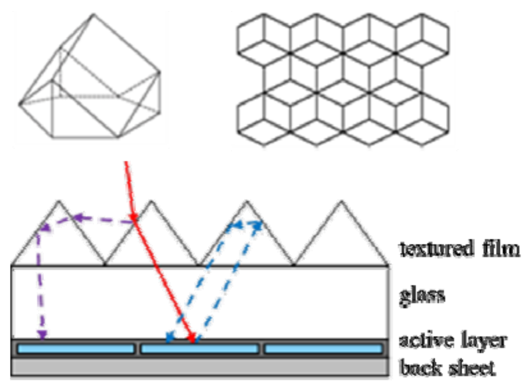


**Figure 1:** (top) Structure of light trapping film. (bottom) Schematic cross-section of PV module with LTF showing the working principle.

planar glass sheets of approximately 365 × 440 $mm^2$. To exclude the effects of the outer edges of the module, the modules were masked with black tape with a rim of 2 mm left open around the cells as shown in Figure 2. A module with single-sided (front) and double-sided application of LTF on the light trapping is compared to the reference situation with extra clear, low iron glass on both sides.

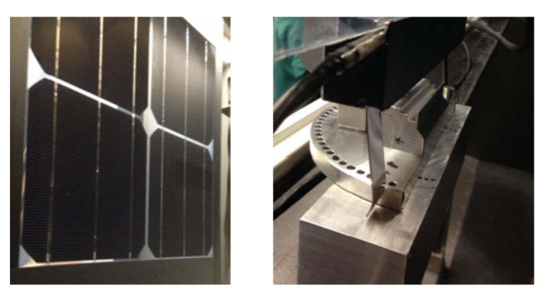

**Figure 2**: (left) Bifacial n-Pasha module, showing the masked aperture. (right) Angular dial used to rotate the module in the Pasan flash tester with 5° resolution.

The modules have been measured in a AAA Pasan SunSim 3b solar simulator. To simulate the effect of sunlight coming from various directions angular measurements have been made inside the Pasan solar simulator. To do so, the module was rotated around its vertical axis between 0 and 85°, with 0° being perpendicular to the light beam (Figure 2).

For the angular dependence of modules with and without LTF, the influence of having albedo light on the rear was investigated by placing white Styrofoam panels (~2 meters behind the module) to simulate high albedo conditions, depicted in the photograph in Figure 3.

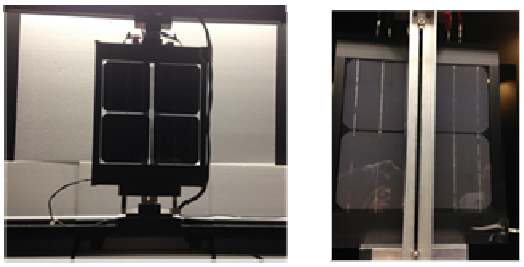

**Figure 3**: (left) Bifacial n-Pasha module in front of the “albedo” created by the Styrofoam panels. (right) Rear view of the angular dial showing that all cells are slightly shaded by the rotating beam

## 2.2 Modelling

The impact of the improved light trapping can be assessed with energy yield modelling. For vertical applications this is especially relevant given the relatively large contribution of irradiation at high incident angles. For the modelling, also the east/west orientation has to be taken into account with respect to standard module geometry (equator-facing) as well as the effect of albedo. The light is modelled according to the anisotropic sky model [2] distinguishing beam and circumsolar diffuse light, isotropic diffuse light and ground reflected light, including shade as depicted in Figure 4.

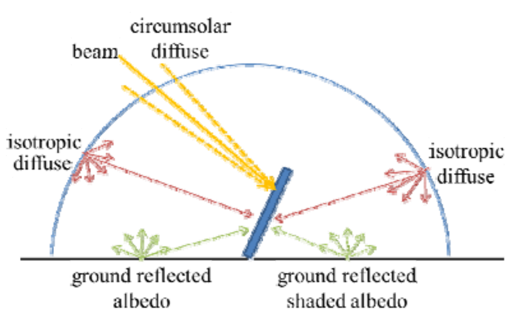


**Figure 4**: Overview of all the light components in the anisotropic sky model. After Duffie and Beckman [2]

A model was set up to calculate the energy yield by summing over the year the power at discrete times. Time resolved meteorological data are used as input for the optical and thermal model. the time resolved output power is obtained by combining these models with the electrical model for the bifacial module. Details of the model can be found in [3]. Note that all three models need to be adapted to get a complete model for bifacial solar cells in a bifacial module.

# 3 RESULTS AND DISCUSSION

## 3.1 Perpendicular incidence

In Table I, the results of the IV-measurements for the 2x2 module are presented for three cases and two situations with perpendicularly incident light. For the analysis of the results, the short-circuit current Isc is used, as it is proportional to the light irradiance and the other IV parameters are only slightly influenced by the changes in light trapping. We have looked at a module without LTF, with LTF on the front and with LTF on both glass surfaces. We measured under STC, i.e. in a room without reflective surfaces behind the module, and also with a scattering background consisting of Styrofoam panels, see Figure 3.

**Table I**: Measured currents with and without LTF (front side or both sides) and with and without high albedo white background panes.

| | Isc @ [A] | Isc @ high albedo [A] |
|---|---|---|
| No LTF | 8.75 | 10.8 |
| Front side LTF | 9.05 | 11.1 |
| Both sides LTF | 9.15 | 11.2 |

The results at angle of incidence θ = 0°, i.e. STC, show that the antireflection function of the light trapping film increases the current of the bifacial module with 3.4%. When applied on both sides an additional gain of 1.1% was measured, totalling 4.5%. This effect is reproduced under high albedo conditions. The Isc with a single, front side LTF is 3.0% higher and with LTF on both sides 4.2% higher. The total bifaciality gain for the module with LTF on both sides, under these specific high albedo conditions, compared to the bare glass module without albedo amounts to a 28% increase in current, including a gain of 23% due to albedo for the bifacial module without film.

## 3.2 Angular dependence

Figure 5 shows the measured Isc as a function of the angle of incidence for double-glass modules without, with front-side and with double-sided LTF. As is expected a rapid decrease in Isc is observed with larger angles of incidence. Upon rotation of the module towards the light, the direct light flux hitting the module diminishes proportional to the cosine of the rotation angle. Figure 5 shows that the addition of LTF increases the Isc with approximately 0.3 A for all angles, with the largest absolute increases observed above θ = 70°.

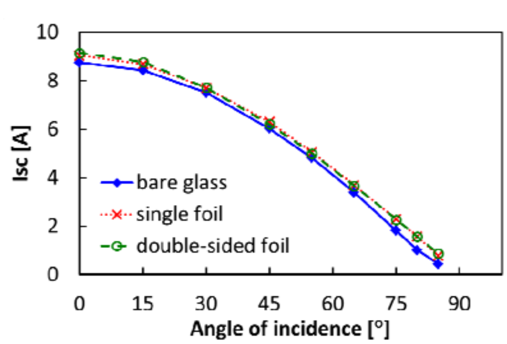


**Figure 5:** Short-circuit current Isc as a function of the angle of incidence θ. The data points for single foil and double-sided foil are almost overlapping

For an analysis of the effect of the angle dependence, the results of the measurements were weighed for incoming flux, i.e. the cosine dependency mentioned above, and corrected for the base reflection of the glass: relative Isc = 96% ($Isc/Isc_{,0}$)/*cos*(θ), where $Isc_{,0}$ is the Isc for bare glass module at zero angle. Resulting relative Isc values are plotted against the angle of incidence θ in Figure 6.

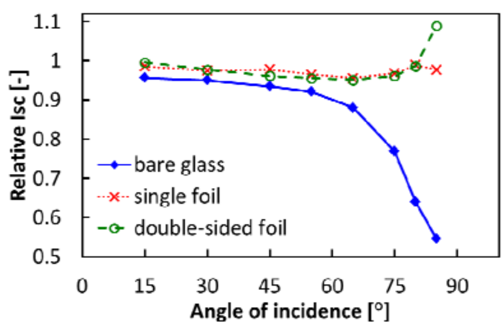


**Figure 6**: Relative Isc, i.e. Isc divided by cos(θ), as a function of θ

As is known from theory, the reflection for flat surfaces increases with increasing angle as observed for the bare glass where the relative Isc gradually decreases from 96% to 90% for θ increasing to 60°. The rate of decrease becomes much larger above 60°, the relative Isc reaching only 55% at 85°. Typically, in modelling of PV modules this angular dependence of the response is accounted for by the angle of incidence (AOI) modifier.

In contrast, the relative Isc of the module with LTF is barely affected. With front side LTF the relative Isc(θ) stays between 99% and 96% from θ = 0° to θ = 85°. Very similar values are obtained for double-sided LTF. This means that by applying LTF, nearly all incoming flux is coupled into the module, independent on the angle of incidence. We attribute the very large value at θ = 85° to a small deviation in orientation. 1° offset will increase or decrease the actual irradiance on the module by about 20%.

3.3 Annual energy yield improvements

We have calculated the irradiance on three model systems, a) a monofacial equator-facing module at optimal tilt, b) a bifacial module at the same orientation and c) a vertical, bifacial module facing east/west. This has been done for Amsterdam, the Netherlands at 52° North and Doha, Qatar at 25° North.

The sum of beam, circumsolar and diffuse contributions is nearly the same for all three systems in Amsterdam. Therefore, any contribution from ground-reflected light makes the light absorption of the bifacial systems larger than for the monofacial system.

In contrast, in Doha the equator-facing systems benefit from the large amount of direct sunlight. Only at high albedo, the increase in ground reflected light is large enough to make the light absorption in the bifacial east/west facing system the largest [3].

To model the AEY gain due to LTF the angle-of-incidence of all incident light contributions has to be taken into account. The relative Isc(θ) starts to deteriorate fast above 50° incidence, see Figure 6. For equator-facing modules about 20% of the light reaching the module is at an incident angle >55°. In stark contrast, for east/west facing vertical bifacial modules 60% of the incident light has an angle of incidence >55°. Obviously, the low AOI-modifier has a negative influence on the AEY for vertical, east/west facing bifacial modules compared to equator-facing modules. Improving the relative Isc(θ), by applying LTF, will therefore have a significant impact on the yearly yield for these vertical applications.

For the contribution from beam and circumsolar light, the angle of incidence is easily calculated at each date and time, and the AOI-modifier can simply be calculated from Figure 6. However, for diffuse and ground reflected light this is more complicated. In that case, an effective angle can be used [2] as given in Figure 7. Here, for both contributions the effective AOI is given as a function of the module tilt β. The appropriate AOI-modifier is obtained by combining Figure 6 and Figure 7.

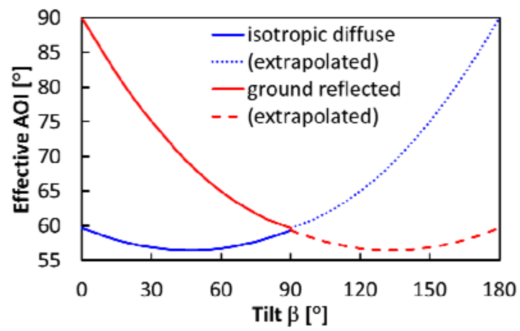


**Figure 7:** Effective angle of incidence as a function of tilt angle β for isotropic diffuse and ground reflected contributions to the incident light [2]. Dashed lines are approximations for the rear side (tilt larger than 90°)

For β = 0° there is no feasible contribution from ground reflected light on the front and the effective AOI is 90°, i.e. infinitely far away. Tilting the module will decrease the effective AOI, until at β = 90°, vertical, the effective AOI is 60°. For the isotropic diffuse light, the effective AOI is 60° for a horizontal module. Tilting the module modifies this value only slightly. The dashed lines are representative for the rear side illumination. For the rear side, the ground reflected light has always an effective AOI around 60°. The effective AOI for the isotropic diffuse light starts also around 60° for a vertical module, β = 90°, but increases monotonically to 90° for a horizontal module, β = 180°, (no diffuse light reaching the module).

Applying the effective AOI and corresponding AOI-modifier to the calculated incident light on the three model systems, the AEY can be calculated. For modules without LTF, the AEY is plotted in Figure 8, showing data for Amsterdam and Doha, at low and at high albedo.

For Amsterdam, both bifacial systems, *south* and *east*, show similarly higher AEY compared to the monofacial system, *mono*. With increasing albedo, the AEY for the east/west facing system increases somewhat faster than for the equator-facing system.

For Doha, the bifacial equator-facing system has higher AEY than the monofacial system, but the bifacial east/west system has lower AEY (grey bar) at low albedo. Whereas the monofacial system is barely changed by a higher albedo, and the bifacial equator-facing system shows the same absolute increase as for Amsterdam, the

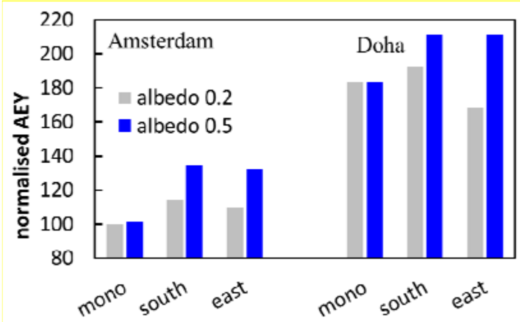

**Figure 8:** Normalised AEY for modules without LTF for the three model systems: *mono* = equator-facing monofacial module; *south* = same for bifacial module; *east* = vertical, east/west facing bifacial module. Equator-facing systems were evaluated at 38° tilt (Amsterdam, left) or 25° tilt (Doha, right)

bifacial east/west system shows a very large increase. The east/west system at high albedo has even the largest AEY of all modelled systems.

To show the effect of the improved relative Isc(θ) of bifacial modules with LTF, in

Figure 9 the relative AEY gain is plotted with respect to the same situation without LTF. For all modelled systems, a 4.5% to 6% increase in AEY due to the LTF is observed. We also calculated the absolute maximum by setting the AOI-modifier for all angles to 1, corresponding to the case that there are no reflection losses at any angle. The gains with LTF make up a large proportion of the theoretical gains of 7.5% to 9% in an ideal anti-reflection film. Data shown here are calculated for an albedo of 0.2. Increasing the albedo has no significant effect on the relative gain in AEY.

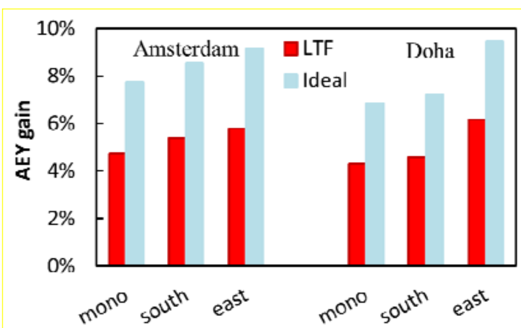

**Figure 9:** Same as Figure 8, but now showing the relative increase in AEY for each situation due to LTF (red) at low albedo. In light blue, the maximum gains are shown, corresponding to no reflective losses at any angle

For the three model systems in Amsterdam, the increase in AEY is more or less the same. The bifacial systems have slightly higher AEY gains due to LTF than the monofacial system, with the east/west vertical system showing the highest gain. For Doha, similar results are obtained as plotted in the right-hand side of Figure 9.

In Amsterdam, the ratio of direct versus indirect light varies only slightly for these three systems. For the monofacial system the ratio is 65:35, for the bifacial vertical system the ratio is 50:50. In Doha, these values are 82:18 and 59:41.

Looking at the differences in more detail, both equator-facing systems show slightly less AEY gain in Doha, compared to Amsterdam. For these systems in Doha, the beam and circumsolar contributions are >75% of the total irradiance. As the average angle of incidence for direct light in these systems in Doha is rather small, the addition of LTF to improve the relative Isc(θ) has less effect than in Amsterdam.

In contrast, for the east/west, vertical system, the isotropic diffuse and ground reflected light makes up a much larger proportion, over 40%, and these contributions are at much higher AOI. Thus the addition of LTF for east/west, vertical modules shows a larger increase.

## 4 CONCLUSIONS

The effect of LTF on bifacial double glass modules has been demonstrated. The STC measurements show an increase in Isc of 3.4% compared to the same module without LTF. Rotating the module showed that, after correction for decreased irradiance, the relative Isc(θ) for modules with LTF is more or less constant up to the highest angles of incidence with the relative Isc >95% for all angles θ. In contrast without LTF, the relative Isc is <90% at θ = 60° and continues to decrease for even larger angles.

Applying these results to an annual energy model for bifacial modules, we have shown that there is a 4.5 to 6% gain in AEY for modules with LTF in Amsterdam. Only minor differences between three different model systems are observed.

For the same three systems in Doha, the AEY gain due to LTF for equator-facing modules is slightly lower as the beam plus circumsolar contributions are by far the largest contribution to the AEY. As these make on average only small angles with the normal of the module plane, the effect of the much better relative Isc(θ) for LTF is of smaller influence. In contrast, for east/west facing vertical modules, the diffuse and ground reflected contributions are a much larger share of the total incident light and have, on average, larger angles of incidence. Therefore, LTF has the largest relative gain in AEY for the vertical east/west system.

## ACKNOWLEDGEMENTS

This work was partially funded by the Dutch TKI Solar Energy project NChanted. www.tkisolarenergy.nl.

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