THE INFLUENCE OF TEXTURED SURFACES OF SOLAR CELLS AND MODULES ON THE ENERGY RATING OF PV SYSTEMS

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➔ Motivation

Beside the need for further efficiency increase of photovoltaic systems, their economic benefit depends on their **energy ratings**. Weak light performance [1], temperature dependence and degradation [2] of PV modules are already well investigated. This work investigates the influence of the **angular dependence of the short circuit current** on the annual yield due to different **surface texturisation** for the cells and the cover glass of the module with a special focus on the reliability of the measurement technique used so far [3][4]. The relative annual energy yields are calculated with an adjusted software tool.

Angle dependence of the Isc: outdoor

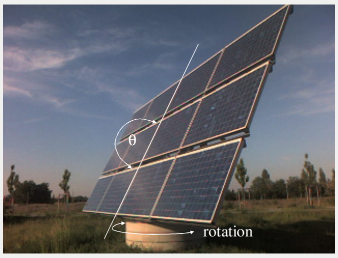

Fig. 1: SOLON Mover in Berlin Adlershof used for outdoor measuremnet of the Isc angle dependence.Twelve 500W modules equipped with Q6M monocrystalline cells and Saint-Gobaint Diamant cover Glass are moved by a 2-axis-tracker.

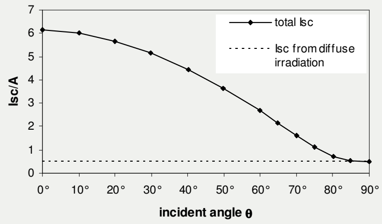

Fig. 2: Angle dependence measured outdoors on the right center module of a SOLON Mover (12 x 500W) equiped with Q6M monocrystalline cells and Saint-Gobaint Diamant cover glass. The elongation was varied between 60° and -30° to the horizontal position at a fixed azimuth position

Angle dependence of the Isc: indoor

	Cell type (texturisation)	glass type (texturisation)
#1	Q6M mono (pyramids)	Diamant (flat)
#2	Q6M mono (pyramids)	Albarino T (weak textured)
#3	Q6M mono (pyramids)	Albarino P (pyramids)
#4	Q6L multi (non-textured)	Diamant (flat)
#5	Q6L multi (non-textured)	Albarino T (weak textured)
#6	Q6L multi (non-textured)	Albarino P (pyramids)

Table 1: Samples with various cell and cover glass texturisation used

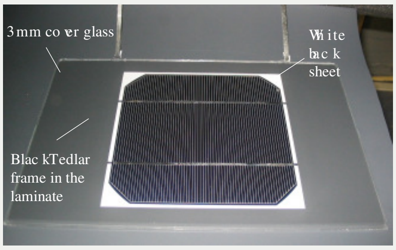

Fig. 3: Single-cell-module with white Tedlar as back sheet and a black Tedlar frame laminated inside with 3mm distance to the cell

Comparison and Correction

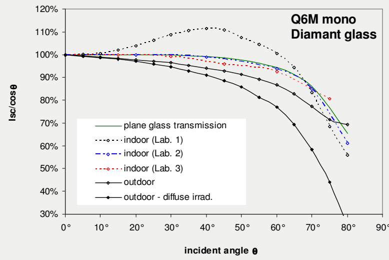

Fig. 4: Indoor measurements on the same system show large differences. The outdoor measurement of Q6M with Diamant cover glass was used as a standard reference after substraction of the non-anle-dependent diffuse component of the irradiation

Re-Calculated results

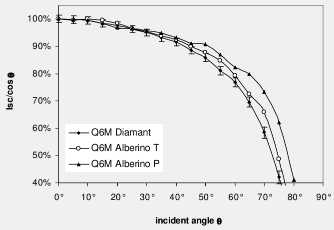

Fig. 5: Q6M mono single-cell modules as used for indoor measurements re-calculated to the outdoor reference standard from Fig. 4

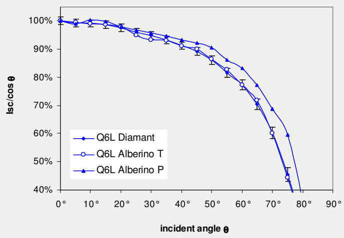

Fig. 6: Q6L multi single-cell modules as used for indoor measurements re-calculated to the outdoor reference standard from Fig. 4

Annual Energy Yields

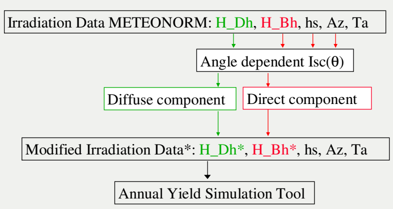

Table 2: Calculation scheme for the aditional consideration of the angle dependent Isc in the annual energy yield

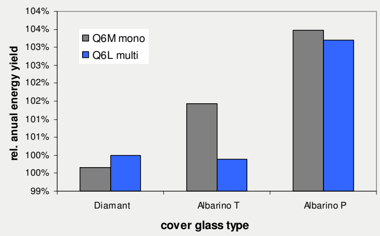

Fig. 7: Relative energy yields calculated for the sytems shown in Fig.5&6. The additional consideration of the angle dependence of the Isc calculates to 10% lower energy yields

➔ Conclusion

- The experimental conditions are very difficult to control for indoor measurements. Therefore only relative variations of the angle dependence should be used from indoor measurements and an outdoor measurement on a identical system should be used as a reference standard.
- The angle dependence of the Isc was integrated in the annual yield simulation by modifying the used irradiation data from METEONORM according to the sun height (hs) and azimuth (Az) given therein.
- Pyramid-like structured glass leads to 3% more annual energy yield compared to flat glass due to an improved angle dependence of the Isc.
- The texturisation of the cells shows no or very little influence on the annual yield for flat and pyramid-like structured glass.

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3. P. Grunow, D. Sauter, V. Hoffmann, D. Huljić, B. Litzenburger, L. Podlowski, 20th Symposium Photovoltaische Solarenergie, Bad Staffelstein, (2005), p. 367.
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ABSTRACT: The energy yield of photovoltaic systems has become a key parameter in addition to its maximum power under standard testing conditions (STC). Commercially available simulation software availableto predict the annual energy yield on the basis of the temperature coefficients, the low light performance and initial module degradation, but do not consider the influence of the angle dependence of the short circuit current of the module yet. Diffuse light accounts for more than 60% of the global irradiation in Europe, and the major share of the direct irradiation incident on the module is non-perpendicular.
This paper investigates the influence of different surface textures on the energy rating of a module as driven by differences in the angle dependence of the short circuit current. The angle dependence was measured on modules with differently textured multi- and mono-crystalline cells combined with flat and textured cover glass. The corresponding annual energy yields were calculated using a modified data set for the hourly irradiation data, which takes the angle dependence into account.
Keywords: energy rating, texturisation, crystalline silicon

1 INTRODUCTION

Beside the need to increase the rated efficiency of photovoltaic systems, energy ratings are the key parameter for their economic benefit. Software simulation programs are widely used to predict the annual yield of photovoltaic systems for a given location. The module parameters therein are the electrical parameters at standard testing conditions (STC) together with their temperature dependence, low light performance [1] and degradation [2] in some cases. All of these module parameters refer to perpendicular irradiation, but incident angles > 0 are pre-dominant under field conditions for non-tracking systems. The angle dependence of the short circuit current is not used as a parameter in the existing software simulation tools, although there has been done a lot of work on annual angular reflection losses [3] and realistic reporting conditions (RRC) [4], including the preparation of an international regulation [5]. This work investigates the influence of the angle dependence of the Isc on the annual yield with a special focus on the reliability of the measurement technique used[6][7]. The relative annual energy yields for chosen sample modules are calculated with an adjusted software tool by modifying the annual hourly irradiation data set.

2 MEASUREMENTS

2.1 Indoor measurements

Six single-cell-modules were prepared using two different cells types from Q-Cells and three different glass types from Saint Gobain Glass, see Table 1. All glass samples were 3 mm thick. The 156 mm multicrystalline cells Q6L were alkaline etched resulting in nearly non-textured surface and the 150 mm monocrystalline cells Q6M were textured in the classical alkaline/ethanol bath resulting in the well-known pyramid structure with a very good texturisation effect. White Tedlar back sheets were used for the encapsulation of the single-cell modules, with black Tedlar laminated inside to form a frame with a surrounding gap of 3 mm to the single cell in the center, see Figure 1. The short circuit Isc of the samples was measured on three different sun simulators each using the same measurement principle for the angle dependence of the Isc, i.e. a measurement stage, which allowed tilting the sample between incident angles θ of 0° (perpendicular) and 90°.

	Cell type (texturisation)	Glass type (texturisation)
#1	Q6M mono (pyramids)	Diamant (flat)
#2	Q6M mono (pyramids)	Albarino T(weak textured)
#3	Q6M mono (pyramids)	Albarino P (2mm pyramids)
#4	Q6L multi (non-textured)	Diamant (flat)
#5	Q6L multi (non-textured)	Albarino T (weak textured)
#6	Q6L multi (non-textured)	Albarino P (2mm pyramids)

Table I: samples for indoor measurements

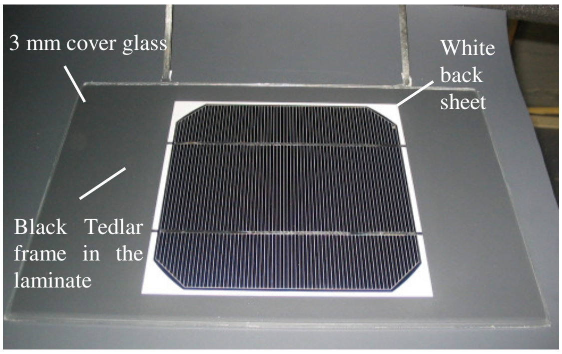

Figure 1: Single-cell-module used for indoor measurements

The measured angle dependences of the Isc were found to be very dependent on the set-up. Possible reasons are misalignment errors of the rotating axis, scattered light from the simulator walls, effects from the non-homogenously illuminated area at large incident angles for large cell areas. Masking the cell from the full area down to a spot of 1 mm² showed differences in the results, when either a vertical tube aperture or a horizontal mask was used. For this reason only relative results were used from the indoor measurements with no additional masking.

2.1 Outdoor measurements

Outdoor measurements were performed with a large 2-axis tracker hosting twelve 500 Watt modules (“Mover” from Solon-PV GmbH). The 500 Watt modules consist of 6 mm Diamant cover glass, white Tedlar back sheet and 80 series connected Q6M monocrystalline cells with a cell-to-cell distance of 3 mm. The angle dependence of the Isc was measured for a center module (Solon SerNo. 217365) from perpendicular to horizontal irradiance in steps of 5° by using the automatic control of the 2 axis tracker in manual mode.

In a second run, the module was rotated in horizontal position around its second axis (“helicopter mode”) to investigate the effect of various orientations between the plane of incidence and the cell edge orientation. The angle of incidence was 40°, i.e. the sun height was hs = 50°.

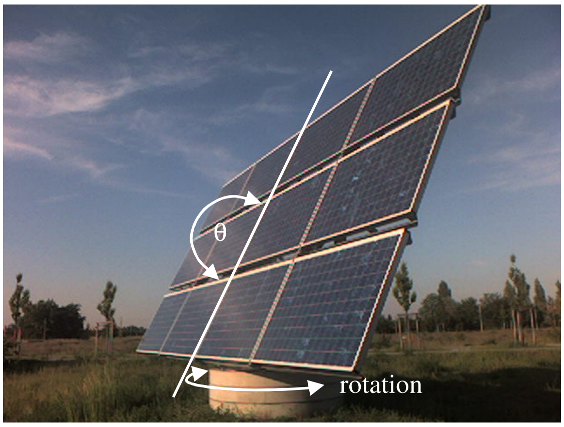

Figure 2: 2-axis tracker used for outdoor angle dependence measurement of the Isc (“Mover” from Solon-PV GmbH; Pmax = 6kW at STC)

3 RESULTS

3.1 Tilt axis orientation

The orientation of the axis showed only minor influence on the Isc, see Figure 3.

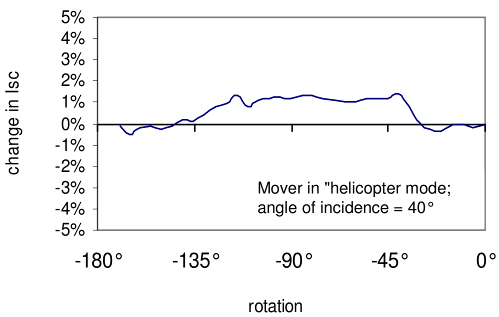

Figure 3: Rotating module under a fixed angle of incidence of 40°, sun height = 50°

For 0° and 180° the fingers on the cell are perpendicular to the plane of incidence. The increase of the Isc for orientations between -45° and -135° by 1% is attributed to the reduced shading effect of the screen printed fingers of the cells, when the plane of incidence is parallel to the fingers. With a 2.1 mm distance between the fingers and a height of 15 µm height this calculates to 0.6% shading loss for the used incident angle of 40° in the perpendicular case. For the sake of unified measurement conditions, all measurement in the following were performed with the fingers orientation perpendicular to the plane of incidence

3.2 Comparison of incident angle measurements

As already discussed, the angle dependence of the Isc depends highly on the simulators used, see Fig. 5 for the system Q6M mono with flat Diamant glass.

The outdoor measurement of the same system was considered to be the most reliable measurement approach for the angle dependence of the Isc because of two reasons:

1. The perfect homogeneity and parallelism of the irradiation under clear sky conditions avoids misalignment and geometric errors even when tilting larger samples.
2. The use of a complete module inside a PV system avoids the effect of undiscovered parameters given by the module design in original scale or the module fixtures.

Figure 4 shows the raw data of the Isc measurement on the Mover in Adlershof, Berlin measured on a sunny day with clear sky tilting the Mover between 60° and -30° vs. its horizontal position. The total outdoor measurement on the “Mover” took 15 min corresponding to a change of 2° in the sun height. The angle of incident was corrected accordingly.

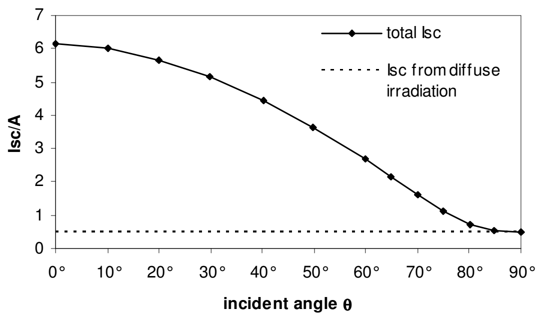

Figure 4: Angle dependence of the Isc measured outdoor on a 500 Watt module of a “Mover” with Q6M monocrystalline cells and Diamant cover glass at 800 W/m²

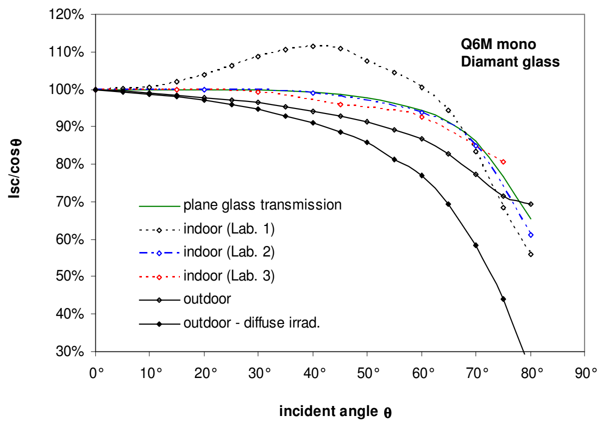

Figure 5: Angle dependence of the Isc for Q6M monocrystalline cells and Diamant cover glass measured indoor at three different laboratories and outdoor on a “Mover” in Adlershof, Berlin, Germany.

The diffuse radiation component and the effect of the illuminated area decrease for the tilted module area in the outdoor data in Fig. 4 were eliminated from the raw data as follows:

$$I_{SC}/\cos\theta = \frac{I_{SC}(\theta) - I_{SC}(90°)}{I_{SC}(0°) - I_{SC}(90°)} \Big/ \cos\theta \qquad (1)$$

For the subtraction of the diffuse component it was assumed that the diffuse irradiation does not depend on the tilt angle of the Mover against its horizontal position between 60° and -30°. Because the collection of diffuse irradiation is most effective for the Mover in the horizontal position, this assumption results in lower values for incident angles around 60°. Using diffuse distribution as given for the reference days in [5] this error was estimated to be lower than 3% absolute in Isc/cos.

In Fig. 5, only the outdoor "Mover" data were corrected for the diffuse component and are used to normalize the relative indoor data in section 3.3.

For comparison, the angle dependence of the transmission through non-textured planar glass is shown in Fig. 5. The measured angle dependence is greater, because of the additional angle dependence of the refection at the encapsulant/cell interface.

The lower IR absorption of the Albarino compared to Diamant glass results in an Isc increase of 1.8% at 0° incidence for 3 mm thick glass. For the same reason, the glass thickness has also an effect on the angle dependence. In the case of Diamant glass the relative Isc/cos θ at 75° incidence is by 2% absolute lower for 6 relative to 3 mm thick glass.

3.3 Angle dependent Isc

Figure 6 and 7 gives the angle dependence of Isc from the indoor measurements on the six sample systems in Table 1 after normalizing to the outdoor data for the Q6M mono Diamant system.

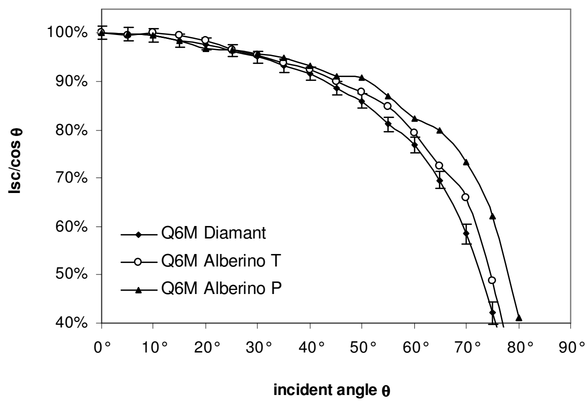

Figure 6: Angle dependence of the Q6M monocrystalline single-cell-modules for different textured glass types

For both cell types the pyramid structured Albarino P glass cover shows a lower angle dependence of the Isc than the flat glass Diamant. This is in good agreement with results reported elsewhere [6] and was explained by the improved geometric optics of the pyramids lifting the incident angle at the cell/EVA interface.

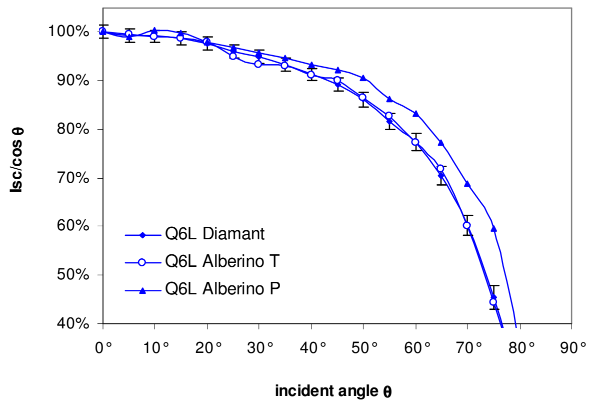

Figure 7: Angle dependence of Q6L multicrystalline single-cell-modules for different textured glass types

The better result for the monocrystalline cells for Albarino T can be explained by its lower IR absorption compared to Diamant. The lower absorption in the infrared gives more benefit for the monocrystalline cells because of their better spectral response in the IR.

4 RELATIVE ANNUAL ENERGY YIELDS

4.1 Calculation

For the calculation of the annual energy yield of the six systems from Figure 6&7, the irradiation data from the data base METEONORM for Frankfurt am Main, Germany were weighted with the measured angle dependence. This gave six different modified irradiation data sets for each specific system in Table 1. These data sets were then used as metrological input data to calculate the annual energy yield with a standard simulation tool.

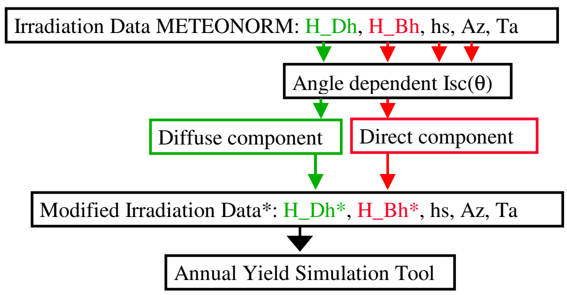

Table 2: Calculation scheme for the effect of the measured angle dependence of the Isc on the annual energy yield

4.2 Comparison

The energy yields for a simulated PV system in Frankfurt am Main, oriented to the south with 30° tilt angle are summarized in Figure 8 and show 3.5% better yields for Albarino P than for the Diamant glass for both cell types.

The better result for the monocrystalline cells when using Albarino T cover glass is explained by the lower infrared absorption of Albarino T (and P) compared to Diamant glass. This gives more benefit to the monocrystalline cells, because of their better spectral response in the infrared. This was not observed for the pyramid structured Albarino P, because the pyramids effectively shorten the optical path and the effect of the reduced IR absorption is decreased drastically.

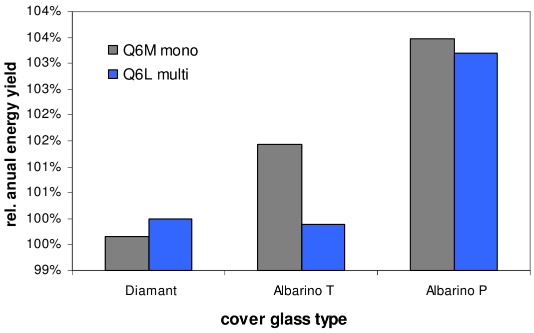

Figure 8: Relative annual yields for all systems at Frankfurt am Main, oriented to the south with 30° tilt angle

In summary, no differences in the energy vields were observed for different surface texturisation for the sample cells used, which were chosen to range from a nearly non-textured surface (multi) to a very effectively textured (mono) surface. The angle dependence of the Isc is mainly affected by the texturisation of the glass and its infrared absorption. For the Diamant cover glass, this result was confirmed by comparing energy yield data from the roof top system at Q-Cells AG in Thalheim, Germany, for module strings with multi- and monocrystalline cells. No significant differences in their energy yields were observed for the period from February to May 2005 inside the tolerances of the monitoring system.

The annual angular reflection losses, i.e. the effect of the angle dependence on the calculated annual yield, is -10% for the Q6M Diamant system, while -3% to -4% was reported earlier for comparable modules in Europe [3]. This is due to the stronger angle dependence found for the outdoor measurements. Further verification of this measurements and its correction are necessary to clarify this deviation.

5 CONCLUSION

The experimental conditions for angle dependent Isc measurements are very difficult to control for indoor measurements. Therefore only relative variations of the angle dependence are used from indoor measurements and an outdoor measurement on an identical system is used as a reference standard.

The angle dependence of the Isc was taken into account in the calculation of the annual yield by modifying the local annual irradiation data from METEONORM according to the sun height (hs) and azimuth (Az).

Pyramid-like structured glass leads to 3.5% more annual energy yield compared to flat glass due to an improved angle dependence of the Isc.

The texturisation of the cells shows none or very little influence on the annual yield for flat and pyramid-like structured glass. Glass with low infrared absorption is beneficial for the angle dependence of the Isc especially for cells with improved spectral response in the infrared.

6 ACKNOWLEDGEMENTS

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