THE IMPACT OF ANGULAR DEPENDENT LOSS MEASUREMENT ON PV MODULE ENERGY YIELD PREDICTION

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ABSTRACT: Different methods to characterize the Incidence Angle Modifier (IAM) of PV modules have been presented in the past [1-4]. From the authors perspective it is questionable if the detailed characterisation of the angular behaviour of PV modules has any significant benefits to yield modelling activities undertaken to forecast the power energy yield of a PV system. The purpose of this work is to evaluate the influence of IAM data from different measurement techniques as input on a yearly yield model. Several sample modules with different top cover such as standard Low iron glass, anti-reflection (AR) coated glass or structured ETFE foils have been characterized on three different test setups, two outdoor and one in the sun simulator. The measured IAM values are fitted to a double exponential model and used in a simple yield model to evaluate the influence of the different measuring methods to the yearly yield for modules with different orientations and different geographical locations. The results show that the different module covers have a significant impact on the IAM, however on yearly yield basis the cosine loss at high angle of incidence (AOI) dominates, reducing the impact of IAM differences. Secondly we show that the AIM characterization is subject of statistical measurement errors caused by the test setup or the module itself. To increase comparability of IAM data we recommend determining a uniform measurement method with precise definition of the test setup.

Keywords: PV Module, Optical Losses, Qualification and Testing

1 INTRODUCTION

The conversion of solar energy in solar modules is subject to electrical and optical losses [5]. Optical losses are substantially depending on light incidence angle relative to the module plane. To minimize reflection losses and thus maximize the electric yield, the PV industry introduced several different concepts and materials, such as antireflective coatings or structured glass with inverted pyramids [6, 7]. Some of those products claim to have better transmission behavior at higher incidence angle than standard low-iron soda lime glass. However, the module characterization at Standard Testing Conditions (STC) only takes into consideration the transmittance of the glass at normal incidence (0°) [8]. Precise characterization methods and measurement systems are needed to assess angular dependent module performance. In this work we compare three alternative methods developed at Fraunhofer ISE to determine the power incident angle modifier (IAM) [9] for PV modules. Feeding the measurement results into a yield model for modules with different orientations and different geographical locations, we investigate the deviation of several measurement configurations to a reference system.

2 INCIDENT ANGLE DISTRIBUTION

The incident angle of the light on a PV module depends on the module orientation, the time of the year and the geographical location. In Figure 1 the incident angle distribution and the yearly direct irradiation in the module plane for a 30° tilted module facing south in Freiburg, Germany is shown. The AOI distribution shows that around 70% of the time the AOI is above 45°. However, due to cosine losses in those operation times with higher AOI, this only corresponds to 29 % of the energy share in module plane [10].

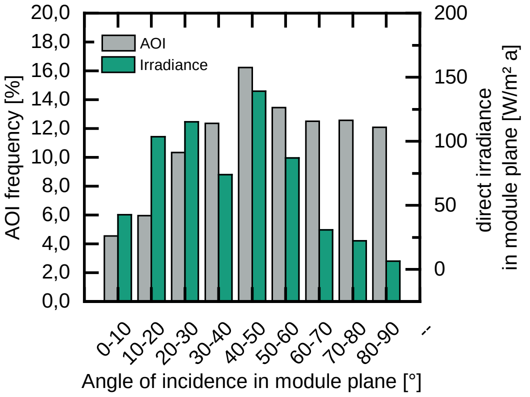

Figure 1: Incidence angle distribution and direct irradiance in module plane over a year for a module facing south tilted 30° in Freiburg, Germany.

3 EXPERIMENTAL WORK

The incident angle modifier for the different modules is measured with three different methods, respectively test setups. Two outdoor and one indoor system are developed and investigated. The systems can further be subdivided into spot irradiation and irradiation of one full cell. The angular incidence effect is measured with the short circuit current which is assumed to be proportional to the light reaching the solar cell and thus the photon generation [7]. The short circuit current is then normalized to the current for normal incidence, enabling a relative comparison between covers having a different transmission at Θ=0°.

3.1 Spot measurement

The light is collimated through a round 2.5 cm x 50 cm collimator to cut off any light with a larger incidence angle than 2.2°. Consequently, the solar module is illuminated on a 2.5 cm spot. When illuminating a solar cell with this method at different angles, a cosine correction to normalize the incoming irradiance is not necessary according to [11]. Due to the small illuminated area the reflections from the module front to the surrounding enclosure are relatively small and therefore the secondary reflection from the darkened measurement enclosure can be neglected. We use the spot measurement for the indoor as well as the outdoor setup.

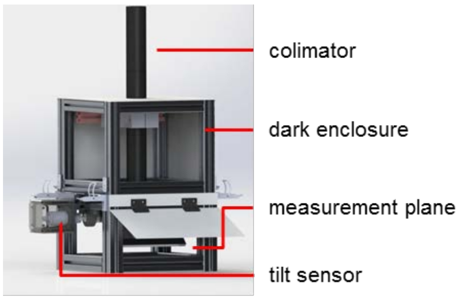

Figure 2: 3D CAD model of the spot measurement setup used on the outdoor tracking system

3.2 One-cell-format measurement

The cross section of the collimator is as large as a one-cell-module (20 x 20cm²) and has a length of 140 cm to cut off most of the diffuse light fraction during outdoor measurement. With this method the measured short circuit current has to be cosine corrected to normalize the currents to the horizontal value. The opening angle of the collimator is 8°. The one-cell-format measurement is used in the outdoor measurement.

3.3 Test locations

The indoor spot measurement consist of a darkened light proof box equipped with a tiltable plane in 1° increments and the mentioned spot collimator. The short circuit current is measured using a PASAN flash sun simulator of grade A at seven different incidence angles from 0° up to 75°.The outdoor test setup consists of a dark box system equipped with a continuously tiltable plane and an accurate electronic tilt angle measurement sensor.

The short circuit current is measured with a continuous angle sweep taking approximately 5 seconds and giving a dataset of more than 100 points. Only measurements where the irradiance intensity stays constant within 5% are used. The DNI is monitored with a Kipp and Zonen pyrheliometer. The measured short circuit current is corrected linearly to 1000W/m²

Figure 3 (right): Image of the one-cell-format test unit mounted on a 2-axis sun tracking system.

Figure 4 (left): 3D CAD model of the one-cell-format measurement unit equipped with a 20x20cm² collimator

4 RESULTS

4.1 Repeatability

To evaluate the repeatability of each system, one module configuration was measured several times. In Figure 5 the share of data points deviating less than 1% of the average for each system and AOI is shown. The strongest deviation is observed for the outdoor one-cell-format system. The sun simulator spot measurement shows excellent repeatability. For all the systems the deviation increases with increasing AOI. This indicates that although huge effort is undertaken to minimize internal reflection of the optical system (dark box) residual parasitical reflections are difficult to avoid. It can be summarized that small light spots reduce the probability of reflection and therefore increase accuracy.

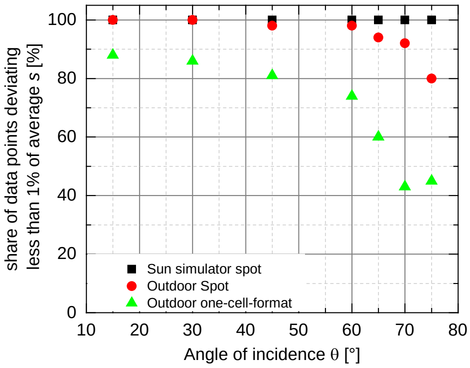

Figure 5: Share of data points deviating less than 1% of average for multiple measurements as a function of AIO plotted for three different measurement systems.

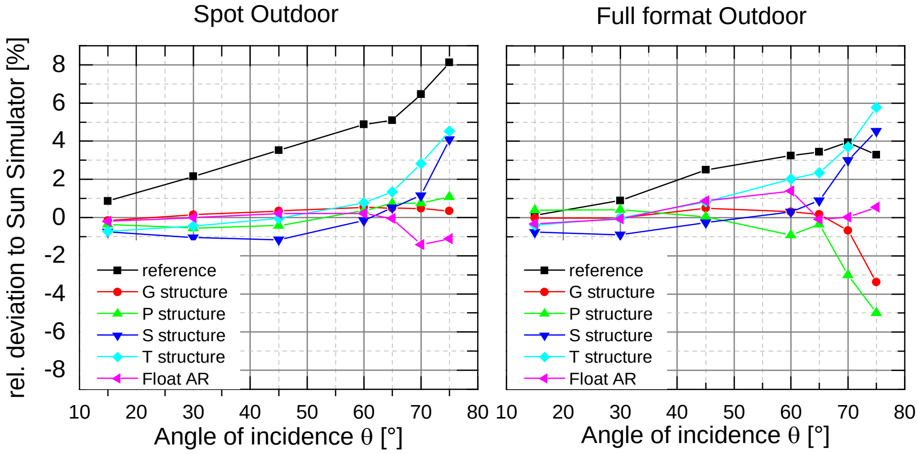

Figure 6: Relative deviation to sun simulator for different top covers and the two compared mesurement setups.

4.2 Measurement differences

Based on the results presented in 4.1 the spot measurement in the sun simulator is taken as a reference and the relative deviation of the two other systems to the sun simulator is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The deviation clearly increases with increasing AOI. Further a higher deviation for flat surfaces is observed than for structured surfaces such as the reference glass or the T or S structured glass, both having microscopic structures. This can be explained with the higher back-reflection in the dark box caused by direct light reflected from the modules. The light from structured surfaces is rather scattered than reflected in one direction which reduces the probability of being reflected directly a second time to the module. The measurement systems with small, well collimated light spots show excellent repeatability for a large range of AOI.

4.3 Yield Model

To evaluate the influence of the different measurement methods on the yearly PV yield a simplified yield model is set up. Model input parameters include: module orientation, sun path, direct normal irradiation, isotropic diffuse irradiation, DNI radiation, ambient temperature, wind speed, module efficiency and power IAM. The yield model does not asses the absolute benefit of AR coated or structured glass but only the relative angular depended differences. Angular depended effects on the voltage, hence on the maximum power are neglected.

The angular incident modifier is fitted to a double exponential model. For the fit the IAM at 90° is set as 1 as boundary condition.

$$IAM(90°) = 1$$
$$IAM(\theta_{\mathrm{ein}}) = \mathrm{a} \cdot \mathrm{e}^{\mathrm{b} \cdot \theta} + \mathrm{c} \cdot \mathrm{e}^{\mathrm{d} \cdot \theta}$$

The diffuse light is modelled with an isotropic model. Taking into consideration the angular dependent reflection of the diffuse light, a mean isotropic angle of incidence modifier is calculated for each module type.

Therefore the visible hemisphere from the modules perspective is dived in segments of 1° x 1° opening angle. The average over the incoming energy multiplied with the attributed AIM is calculated.

$$F_{\mathrm{IAM}} = \frac{\sum_{n=0}^{n_{\text{visible segments}}} IAM(\theta_{\mathrm{segment}})}{n_{\text{visible segments}}}$$

The module temperature is modelled with a simple approximation according to Kratochvill [12].

$$T_{\mathrm{mod}} = T_{\mathrm{amb}} + E \cdot \exp[-3{,}473 - 0{,}0594 \cdot v_w]$$

The module power is calculated with the cosine corrected direct irradiance and the diffuse irradiance in module plane. The annual energy yield is calculated for 1h time intervals with input data taken from the weather database Meteonorm [10]. The module power temperature coefficient is set as -0.38%/K and the module efficiency is assumed to be 16%

$$E_{direct,plane} = DNI \cdot \cos\theta_{AOI}$$
$$E_{plane} = \left[E_{direct,plane} \cdot IAM(\theta) + E_{Diff,plane} \cdot F_{AIM}\right]$$
$$P_{\mathrm{mod}ule} = E_{plane} \cdot (T_{\mathrm{mod}} \cdot \alpha_P) \cdot \eta$$
$$W_{year} = \sum_0^{8760} P_{module} \cdot t$$

In Figure 6 the relative difference in yearly yield in comparison to the reference measurement system (spot sun simulator) for the AR coated, the G structured and the reference glass measured with the two non-reference measurement systems is shown for two module tilts at two different locations. It appears that the yield gain is extremely sensitive on the module tilt. In practice the yield is extremely sensitive on the share of irradiance at higher angle of incidence. As the share of high angle of incidence increases for higher module inclination angles in our latitude level (e.g. vertically mounted BIPV module), this leads to strong differences in yield. For 30° tilt the difference ranges from around -0.5% to +2% whereas the different ranges from 1% to 6% for vertical installation. It can be observed that the glass with the highest reflections (standard float glass) is subject to the largest differences. For the structured and AR coated glasses the difference between the systems does not exceed 3%. This is a result of the positive effect of antireflective structures or coatings.

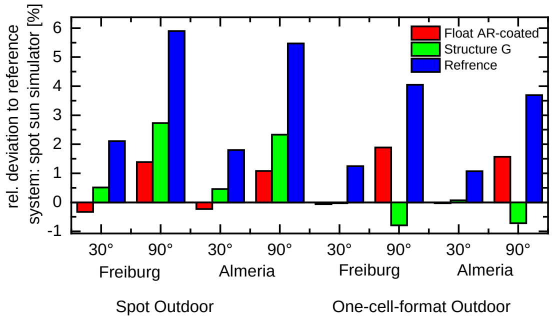

Figure 6: Relative deviation of yearly yield to reference measurement system for Freiburg and Almeria.

5 CONCLUSIONS

Our results show that the angular response of different PV modules with different top covers differ significantly from each other, especially at angles of incidence above 45°, independently from the measuring method. The measuring results obtained by the investigated methods differ significantly for AIO above 60°.

However the calculated effect on the yearly yield for standard module orientations (e.g. 30° South) is not of significant impact. This is mainly due to the fact that for typical module orientations with increasing AOI the solar irradiance in the module plane decreases and the cosine losses dominate. Only for special module orientation such as vertically mounted modules in BIPV a significant energy yield difference between the systems of up to 6% is calculated with the measured AIM data. Therefore, we conclude that a deep understanding and a detailed characterization of modules regarding their angular behavior is of great importance for special orientations, but less import for standard orientations. Further we conclude that the measurement method has little impact on the IAM hence on the yield prediction. However, the IAM measurement may be subject to severe uncertainty depending on the test setup and the module cover being characterized. Therefore a standardized characterization method similar to the standard testing conditions for power rating would bring significant benefit.

The standard should limit secondary reflection for the dark box or the size of the light spot to be used for IAM characterization. The obtained IAM data from such a standardized test setup could then be used for comparison of different module configurations.

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