Glare Hazard Analysis of Novel BIPV Module Technologies

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Abstract

Standard Photovoltaic (PV) modules use anti-reflective (AR) surfaces or coating to maximise solar energy transmission and minimise reflection (Hartmeyer, 2019). Despite this, they can still create glare hazards. New PV modules have been developed for building-integrated photovoltaics (BIPV) to lessen the possibility of glare hazards. In this paper, an outdoor measurement technique for evaluating glare hazards of PV modules is introduced. Eight different PV module glass technologies and coating technologies are tested and compared. The results show that by reducing specular reflection and increasing beam spread, the relevant measure of glare (luminance) can fall by several orders of magnitude without reducing the performance of the PV modules.

Keywords: glare hazard, beam spread, luminance, specular and diffuse reflection, PV modules, solar glass

1. Introduction

Glare hazards caused by PV modules can be a relevant issue, primarily for circumstances where PV systems are built in the vicinity of airports (Ho et al., 2015). Although, several instances of PV systems built close to runways succeed in not increasing safety risks for aeroplanes. Glare hazards are also relevant in neighbourhood areas. Swissolar, the Swiss PV association, reports an increasing number of neighbour disputes due to glare effects from PV systems. South-facing PV systems in the northern hemisphere are normally not critical. East and west-facing systems can cause glare hazards to neighbours east and west of the system, mainly shortly after sunrise and before sunset. Though, due to the short duration of the glare hazard, these systems are also usually not too problematic. However, north-facing systems are often critical if neighbours are located north of the PV system.

In Switzerland, there have been various court cases dealing with glare (Bohren, 2015 and Stickelberger, 2021). One of the difficulties is that the law knows neither limits for glare duration nor glare intensity. Therefore, case law on these matters is unpredictable.

In various older publications, the terms ´glare´ and ´reflection´ are not clearly distinguished (Shields 2010, Shea 2012). In the Swiss ´Raumplanungsverordnung´ (RPV 2021), PV systems must be designed with low reflection according to “state-of-the-art” to avoid the need for a building permit. Consequently, a conflict arises: while most PV modules are optimised for low reflections (e.g., through using AR coating), only a few are designed for low glare. AR coated modules will not necessarily reduce glare hazard risks but could increase them (Ruesch 2015).

This paper gives relevant definitions of glare hazards and related terms (see chapter “2. Fundamentals of Glare Hazards”). Additionally, an outdoor measurement procedure is investigated to evaluate the glare potential of single PV modules and entire PV systems (see chapter “3. Methods to Measure Glare”). The method is tested using different module technologies and different measurement distances.

The measurement results of three PV module types, available on the market, and five prototypes are presented and evaluated. Mathematical functions to characterise the glare properties of these modules are proposed.

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2. Fundamentals of Glare Hazards

2.1 Literature review on glare hazards

In DIN EN 12665:2018, glare is defined as an uncomfortable visual condition due to unfavourable luminance distribution or excessive contrast. However, no limit values are given. In Wittlich (2010), a differentiation between absolute glare and relative glare is made. *Relative glare* is mainly based on high contrasts, while *absolute glare* is defined as the saturation of the eye, which occurs between luminance values between 10´000 cd/m^2 and 1´600´000 cd/m^2 (Wittlich, 2010).

In the SGHAT tool derived in Ho (2011, 2015), the relevant measure for glare is given by the retinal irradiance in W/cm^2 and by the subtended source angle in mrad. The larger the subtended source angle, the smaller the retinal irradiance limit for *potential for after image* or even *retinal burn*, according to SGHAT.

Luminance in cd/m^2 indicates how bright a surface is from the point of view of an observer. The relevant measure used in this paper is luminance in cd/m^2 (Wittlich, 2010, Ruesch 2015). Measurements carried out by the authors of this paper show that the highest luminance levels for diffuse reflectors (a white wall in the sun) are in the range of 20´000 to 30´000 cd/m^2. Similar results have been found in Ruesch (2015).

2.2 Definitions used in this paper

Due to the unclear nature of the definitions and limits for glare given in the literature and legal documents, the following definitions are used:

- Glare is defined as a disturbing reflection.
- Glare occurs if the luminance of a reflection is > 50´000 – 100´000 cd/m^2.

Note: the above definitions may only be appropriate in the context of this paper and not as general definitions for the terms.

The second value is chosen based on the literature research and the authors´ experience in the measurements carried out for this paper. While 25´000 cd/m^2 in a bright environment does not necessarily cause glare, reflective surfaces of 100´000 cd/m^2 and more appear too bright to look directly into, even if the eye gets momentarily adjusted to a bright environment.

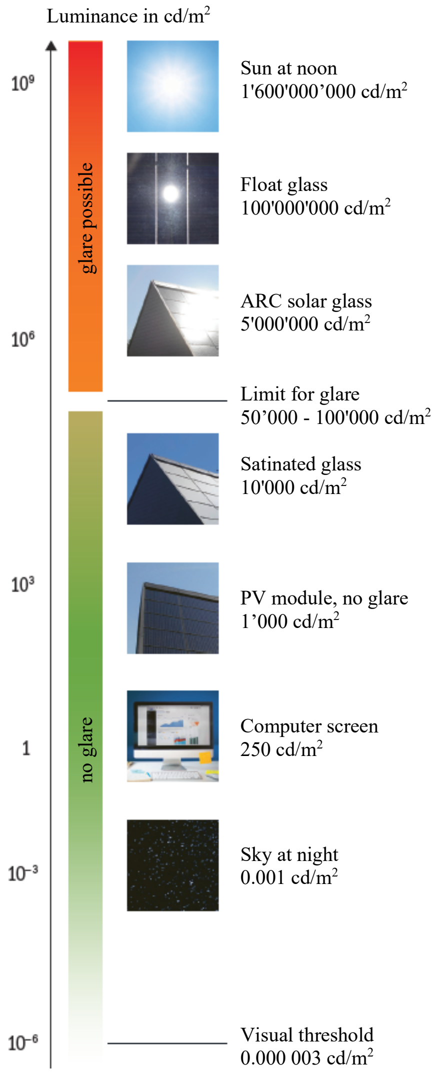

Fig. 1: Luminance of different surfaces.

2.3 Glare hazards on PV systems compared to other glare hazards

Glare hazards can occur in many built-up environments and on various surfaces, but the severity differs in some aspects from glare hazards on PV modules:

- Since PV systems typically cover large areas, glare hazards can last a long time. Severe glare hazards can last for several hours a day. Whereas in built-up environments, the glare hazards of other surfaces such as roof windows usually last only a few minutes.
- For the same reason, it is difficult to avoid the beam of glare once it occurs. While the beam of glare from a conventional roof window glass is limited to about one or two square meters, the beam of glare from PV systems can affect a whole sitting area or garden.
- On the other hand, glare hazards on PV systems are often much weaker than glare hazards on other surfaces such as conventional window glass.

Fig. 1 gives an overview of several surfaces and their luminance.

The luminance of a reflecting surface does not primarily depend on its reflection coefficient but the specularity of the reflection. Assuming that a mat, white surface with a reflection coefficient of 1.0 does not cause any glare due to its diffuse reflection behaviour, only specular or partly specular reflection can cause glare hazards (see Fig. 2).

To reduce the glare properties of a surface, it is not necessary to reduce the reflection. The glare properties of a surface can decrease by widening the reflection beam (beam spread). The PV modules tested in this paper (which cannot cause glare hazards unless in specific situations) have relevant beam widening properties.

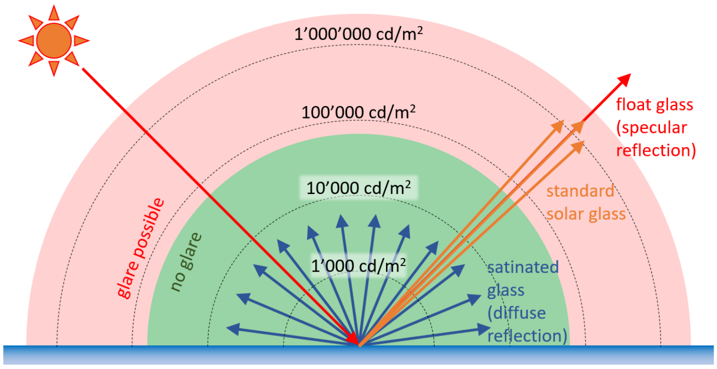

Fig. 2: Effect of beam spread on the luminance of a PV module.

3. Methods to Measure Glare

3.1 Indoor laboratory measurement of glare

A precise way to measure the reflection properties of surfaces is described in Ruesch (2016). The Bidirectional Reflection Distribution Function (BRDF) describes the reflecting luminance of a surface as a function of all possible angles of incidence, reflection angles and the illuminance in Lux. To measure the BRDF, the surface in question is illuminated with a light beam under all relevant angles. The reflection is captured using a hemispheric screen, and a camera is used to measure the screen's luminance.

The BRDF gives a holistic picture of the reflection properties of a surface such as a PV module. However, it is neither possible nor necessary to measure a BRDF of a whole PV installation. For this purpose, on-site glare measurements using a luminance meter or camera is more suitable.

3.2 On-site measurement of glare

On-site measurements are done during the glare period under clear-sky conditions. The results are not as holistic as the BRDF laboratory measurements and less accurate and repeatable, but they provide two main advantages:

- No changes/manipulations at the PV system are necessary.
- The measurement setup and results capture exactly the situation which is visible at the observation point.

In this paper, an on-site measurement method to measure the possible glare of a PV system is investigated. The precision of the measurement method is estimated using an outdoor laboratory setup.

Measurement devices

The following measurement devices are used in this paper:

- Gossen MAVO SPOT 2 USB: luminance meter
- ND1000 Neutral Density Filter: lowers luminance by a factor of 1000

Fig. 3: Calibrated luminance measurement device MAVO SPOT 2 used for glare measurements (left). View through the lens of MAVO SPOT 2 (right). The circle in the centre of the measurement spot covers an angle of 1°.

Independence of Distance

The reflection of the busbars of a PV module can falsify the measurement results. The reflection due to the busbar occurs when the distance between the measurement device and the module is too small, causing the busbar to occupy a big amount of the measurement field of 1°. The negative effect increases if the glass under examination shows a comparatively low luminance, which results in a higher dominance of the busbar's reflection. Fig. 2 shows that the variability of measurement results decrease a lot if the distance between the measurement device and the module is 2 meters or more (green area).

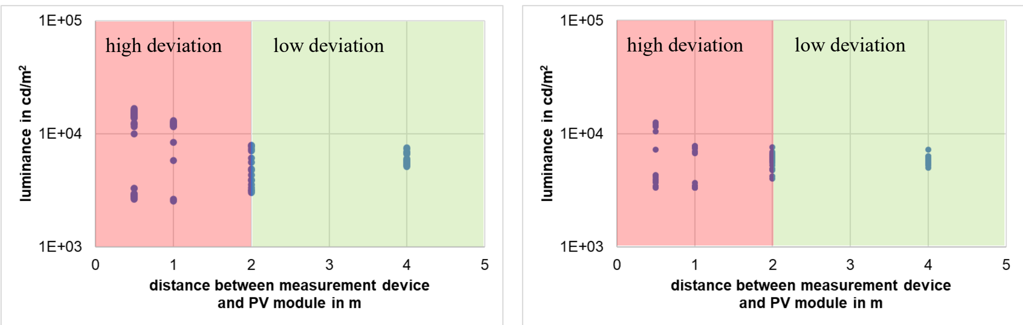

Fig. 4: The luminance measurement is inherently subject to relatively large variance. However, the variance increases a lot when the distance between the measurement device and the module under test becomes too short and only a single busbar is within the measurement area of the luminance measurement device (red area). Left: incident angle = 10°. Right: incident angle = 45°.

The module that showed the lowest luminance (satinated glass) is examined to determine the minimum required measurement distance. If the busbars show no relevant reflection at a certain distance, their influence is even lower for glasses with more specular reflection properties.

The measurement results show maximum values around 7000 cd/m^2 at distances of 2 m and larger. At shorter distances, some values are a lot higher due to the dominance of the reflections of the busbars.

It is proposed to cover at least two busbars with the measurement device to minimise their dominance, as shown in Fig. 5.

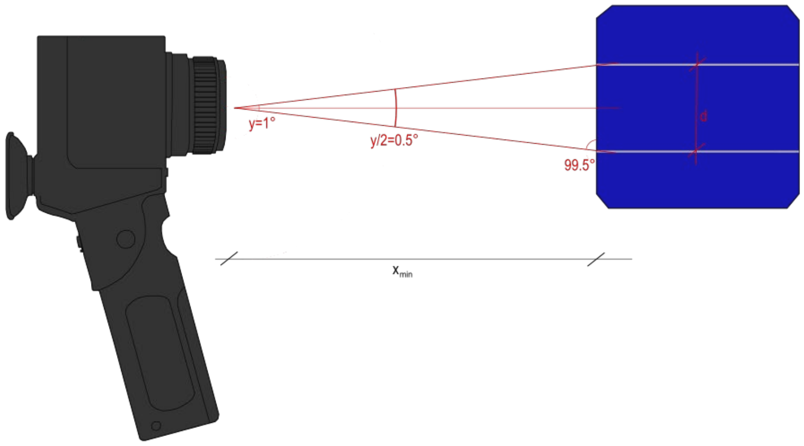

Fig. 5: If the measurement captures at least two busbars, the busbars will no longer falsify the measurement.

Distribution of measured values

Due to inhomogeneities in the luminance of the module surfaces and due to the manual measurement procedure, the luminance measurements are subject to a lot of noise and outliers. Misalignment of the measurement device, which cannot be avoided in practice, leads to big measurement deviations. Therefore, raw data is filtered with the following outlier detection algorithm:

$$\begin{array}{ll} data\ used & > Q_{65} \\ outliers & all\ other\ data \end{array} \tag{1}$$

where Q_{65} is the 65% quantile of the data. The quantiles are calculated using 10 values before and 10 values after the given luminance values (sliding quantiles). The single-sided filter was chosen because all outliers have lower values than the expected values. The results of the data filtering process are shown in Fig. 2.

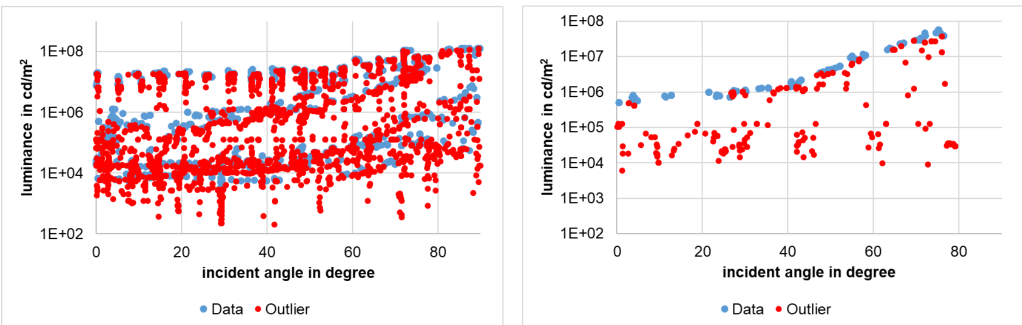

Fig. 6: Raw data from the luminance measurements of all PV modules (left) and the standard PV module only (right). Outliers are marked in red.

3.3 Empirical function to describe the glare behaviour of PV modules

To describe the measurements, the following functions are proposed. The functions fit the common logarithm ($\log_{10}$) of the luminance:

$$y_1 = a \cdot x^4 + b \cdot x^2 + c \tag{2}$$

$$y_2 = b \cdot x^2 + c \tag{3}$$

$$y_3 = spline \tag{4}$$

y_1 is a symmetrical fourth-degree polynomial function (biquadratic) and y_2 is a symmetrical square function (quadratic). These functions were chosen because they are symmetrical and have similar shapes to the measurement data. The vertex is at x=0. y_3 is a natural cubic spline with two internal knots. Due to the high number of adjustable parameters y_3 is assumed to give the best possible fit. y_3 is therefore used as the benchmark for the highest expected coefficient of determination R^2. y_1 and y_2 are relatively simple functions having only 3 and 2 parameters, which is less accurate but beneficial for the practical use of the equations.

The quality of the fit measured by the R^2 varies a lot for different measurements. The biquadratic function is beneficial for some measured curves but not for all. Fig. 7 shows the fit for a standard PV module and a satinated module as two examples. For the satinated module, the coefficient of determination of the biquadratic equation is clearly better than that of the quadratic equation.

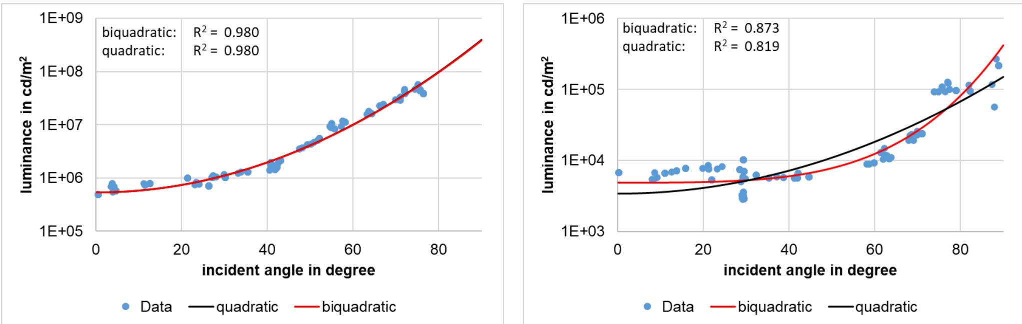

Fig. 7: Quality of fit depending on the module technology. Left: Standard PV module. Right: Satinated PV module.

4. Results

4.1 Comparison of different solar modules

The luminance measurement results of all tested PV modules are shown in Fig. 8. The parameters found for the measurements and their coefficient of determination are given in Tab. 1. The coefficients of determination are compared in Fig. 9.

Generally, both the quadratic and the biquadratic functions are suitable to model the luminance data of the various PV modules.

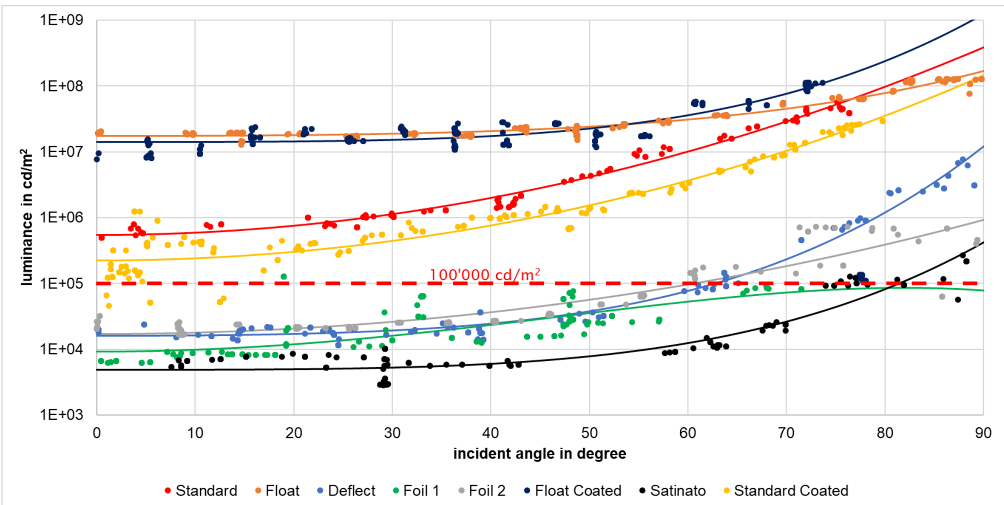

Fig. 8: Luminance measurement result of different PV modules including best fit functions.

Tab. 1: Parameters derived for the functions in Fig. 8.

	$y_1 = a \cdot x^4 + b \cdot x^2 + c$				$y_2 = b \cdot x^2 + c$			*spline*
Name	**a**	**b**	**c**	**R^2**	**b**	**c**	**R^2**	**R^2**
Deflect	3.69E-08	5.70E-05	4.20	0.981	3.22E-04	3.99	0.935	0.988
Float	1.16E-08	2.75E-05	7.25	0.966	1.10E-04	7.17	0.919	0.976
Float Coated	2.83E-08	1.14E-05	7.15	0.808	1.56E-04	7.06	0.753	0.855
Foil 1	-2.14E-08	2.88E-04	3.97	0.565	1.99E-04	4.01	0.551	0.628
Foil 2	1.10E-09	2.05E-04	4.23	0.865	2.12E-04	4.23	0.865	0.887
Satinated	2.80E-08	1.23E-05	3.69	0.873	2.03E-04	3.53	0.819	0.900
Standard	-2.33E-11	3.53E-04	5.73	0.980	3.53E-04	5.73	0.980	0.987
Standard Coated	2.22E-09	3.29E-04	5.35	0.906	3.40E-04	5.35	0.906	0.911

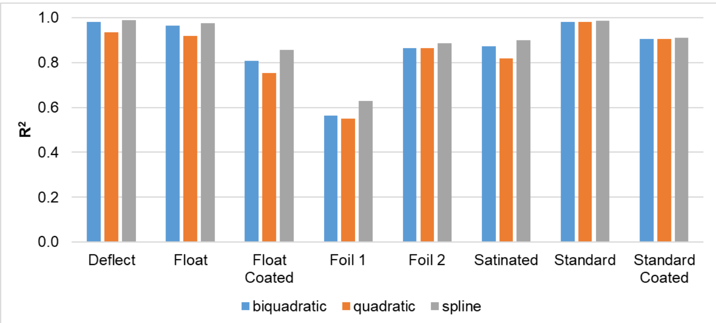

Fig. 9: Coefficient of determination R^2 values for the functions fitted to the data.

4.2 Case study: Replacement of standard PV modules with satinated PV modules

A north-facing roof-integrated PV system with PV modules made of standard solar glass caused glare effects on the neighbouring garden and living room. The glare effects were quantified for several weeks in summer and up to 2.5 hours per day.

The luminance of the PV modules, installed in 2016, was measured on-site by the BFH PV laboratory on a cloudless day in June 2021. In a test setup, four of the modules have been replaced by satinated PV modules. The measured luminance values are reduced by a factor of around 1000 and are well below the limit of 50´000 – 100´000 cd/m^2 mentioned in chapter "2 Fundamentals of Glare Hazards" (Fig. 10).

The appearance of the old and the new PV modules are shown in Fig. 11. It can be concluded that the satinated PV modules eliminated the glare hazards.

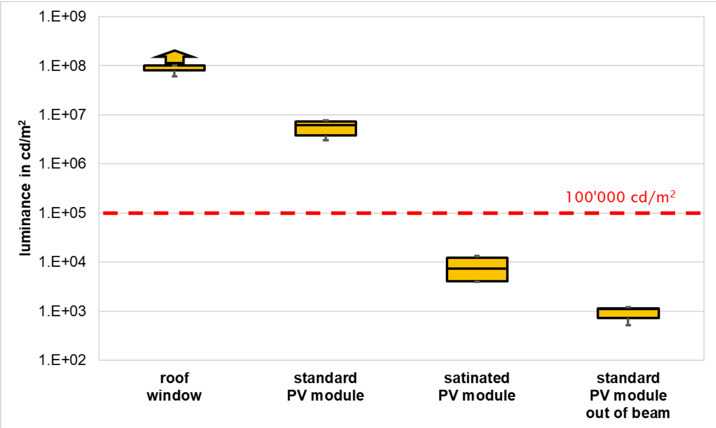

Fig. 10: Measurements of the reflected beam from the roof window, the standard PV module, the new satinated PV modules and the standard PV module out of the reflected beam.

Fig. 11: Roof-integrated PV system with standard solar glass modules (left), four satinated modules for testing purposes (middle) and fully covered with new satinated PV modules (right).

5. Conclusion and Outlook

Two main conclusions can be drawn from this paper:

1. The glare potential of different PV modules largely varies. New module surface technologies such as satinated glass or glass coated with a foil can reduce or even eliminate the risk for glare hazards.
2. The luminance of module surfaces can be measured in the laboratory or on-site. Outdoor measurement results are subject to high level of noise. Filtering the data increases the data quality and makes it possible to present the results in a simple quadratic or biquadratic form.

The measurement results in this paper do not yet fully explain the phenomenon of glare. The reproducibility and reliability of the measurement method must be further investigated and proven in future research projects.

Since these anti-glare modules are relatively new on the market and only little experience with glare measurements is reported, some research is still required to fully understand their possibilities and limitations. Hence future research questions are:

- How robust is the outdoor measurement procedure regarding meteorological influences? What are minimum requirements for both the measurement procedure and the meteorological conditions during the measurements?
- How do the outdoor measurement results correlate with BRDF measurements done in the laboratory? The BRDF gives one 3 dimensional function for every angle of incidence, whereas the method presented in this paper limits the reflection characterisation to one dimension only (one number for every angle of incidence). What is the error which has to be expected with this method?
- Are the proposed functions for describing glare properties generally valid for all possible PV modules?

And are they useful to characterise PV modules in terms of their glare properties?

- How do the optical properties of anti-glare modules change over time?

6. Acknowledgments

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