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# LIGHT REFLECTION ANALYSIS OF PV MODULES: COMPARISON TO BUILDING FACADES AND ASSESSING THE POSSIBILITY OF GLARE

Janina Moereke[1], Peter Borowski[1], Stefan Grünsteidl[1], Jörg Palm[1], Subarna Babu Sapkota[2] and Thomas Dalibor[1]
[1]Avancis GmbH, Otto-Hahn-Ring 6, 81739 München, Germany
[2]Avancis GmbH, Solarstraße 3, 04860 Torgau, Germany
Phone: +49(0) 89 219620 442, Email: janina.moereke@avancis.de

ABSTRACT: Light reflection measurements have been performed on several PV modules as well as a range of passive façade materials. The measurements have been performed in specular direction according to DIN EN ISO 2813 and resulted in the confirmation of very matt appearance for special façade PV modules compared to commonly used building façades. BRDF analysis of these façade PV modules further showed the absence of a specular reflection peak compared to glossy samples and established maximum reflection to occur at reflection angles above 80° to the normal of the module and in-plane with light incidence. Luminance estimations suggest that levels of absolute glare are only reached with both maximum Sun irradiation as experienced on Earth and geometries of maximum reflection. Since these geometries and irradiances occur for an observer of a south-facing façade BIPV installation only in the morning and evening hours, the risk of glare from the analysed façade PV modules is considered negligible.

Keywords: Building Integrated PV (BIPV), Façade, Solar Architecture, Glare, CIGS

## 1 INTRODUCTION – GLOSS AND GLARE IN BIPV

As photovoltaic (PV) modules are being integrated into urban structures such as building façades, the importance of the visual appearance of the modules increases and the question of gloss or how strongly light is reflected from PV modules has become relevant not only regarding yield, but also regarding potential risks and disturbances in urban environments through glare. Especially for environments such as airports, glare assessments are part of safety hazard prevention [1]. In urban environments the oversight of assessing how a structure may reflect sunlight has made headlines in the past, even mentioning sun rays being reflected at such strength that surrounding buildings and parked cars had been damaged [2][3][4].

Glare describes the phenomenon when the human eye is no longer able to adjust to the brightness of the incoming light, in the case considered here, the light reflected from the PV module's front glass. Among other measures, front glass design options aiming to increase transmittance and avoid reflection have been explored [5][6]. As a result, a variety of PV modules is available that differ in their material properties, especially regarding their visual appearance. However, the assumption that light is reflected as strongly from all PV modules as from other glazing is still common when assessing the risk of glare and represents an obstacle in encouraging the use of PV modules by architects and planners [7][8]. As a consequence, solutions for reducing the risk of glare often address only the orientation of the modules [9]. However, since a diversity of technologies and design options exists for building-integrated PV (BIPV) installations, a more rigorous analysis of the reflection behaviour of PV modules is of interest.

A previous study has assessed light reflection focusing on the specular case, for which classifications for glossiness exist from other industries [10]. Others have included a more detailed analysis of light reflection by performing experiments across a range of angles and recognized that there is currently no universally accepted evaluation method for the risk of glare from PV modules [11]. The present study goes a step further by combining the two methods and putting the results into context in the building industry: making use of the speed and ease of gloss measurements to compare PV modules with commonly used non-PV façade materials, but also providing thorough information regarding light reflection from a highly matt PV surface using BRDF (bidirectional reflectance distribution function) measurements. Together with actual measurements of glare on a BIPV façade, concerns of disturbing or dangerous levels of light reflection when using PV modules in urban environments are addressed, particularly in comparison to conventional non-active building materials and façades.

## 2 EXPERIMENTAL METHODS

Two methods were used to assess light reflection from PV modules. Specular reflection, i.e. when the angle of reflection equals the angle of incidence, was compared for different materials, while scattered reflection was analysed for our SKALA BIPV module. SKALA is a thin-film CIGS PV module available in different colours. It has been designed specifically for the use in façade installations in urban environments.

### 2.1 Gloss measurements

The way in which light is reflected from a material or a surface results in a visual impression that is described across different industries using terms such as "glossy", "semi-glossy" or "matt". While these terms are often used without a clear definition of how much and in which direction light is reflected, a standard has been created in the coating and varnish industry [12] relating these terms of visual impression to measurements of light reflection. The norm describes a standard procedure defining measurement and incidence angles. Comparable results are achieved with this measurement procedure and enable the assessment of different materials according to their glossiness. Gloss measurements are performed only in specular direction, i.e. at measurement configurations for which the angle of incidence equals the angle of reflection (see an illustration of the measurement setup in Figure 1).

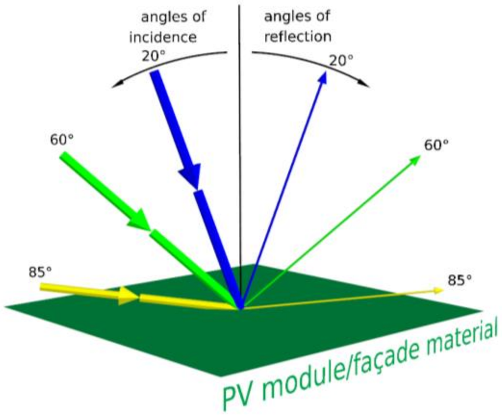


**Figure 1.** Angles of incidence and reflectance used in gloss measurements. Only specular reflection, where the angle of incidence equals the angle of reflection is assessed in this measurement setup.

Specular reflection is measured at three distinct angles: 20°, 60° and 85°. Results are given in gloss units (GU). The gloss units scaling is defined using light reflection from a perfect mirror and defining the equivalent gloss values to be 2000 GU, 1000 GU and 199 GU at 20°, 60° and 85°, respectively, for the measurement equipment used in this study. The measured gloss value of a material can therefore be converted back into percent reflected light using the conversion factors listed in Table I. Since these values are based on the reflection from a standard material as defined in [13] rather than a manufacturer specific definition, an independent publication derives factors differing in the decimal places [14]. For this study the factors provided by the equipment manufacturer have been used since the measurement equipment was calibrated as such by the manufacturer.

**Table I:** Conversion from gloss units to percent reflection according to the equipment manufacturer and [14]

| Measurement angle | % reflection (acc. to equipment manufacturer) | % reflection (acc. to [14]) |
|---|---|---|
| 20° | GU(20°)/20 | GU(20°)/20.376 |
| 60° | GU(60°)/10 | GU(60°)/9.994 |
| 85° | GU(85°)/1.99 | GU(85°)/1.674 |

**Table II:** Gloss measurement angle according to [12]

| Gloss value at 60° | Measurement angle according to [12] |
|---|---|
| <10 GU | 85° |
| 10-70 GU | 60° |
| >70 GU | 20° |

While the measurements were performed at three different angles, only one value will be quoted as the sample's gloss value, depending on the value measured at 60° and according to the standard (see Table II). For very matt samples (<10GU at measurement angle of 60°), a measurement angle of 85° is used, while for highly glossy samples (>70GU at a measurement angle of 60°) the measurement angle of 20° is most appropriate.

Measurements were performed using the glossmeter Rhopoint IQ-S. This handheld equipment measures light reflection in accordance with the previously mentioned standard [12] and converts percent reflection automatically into GU as defined in Table I (middle column). Measurement results were available in GU only. The manufacturer states that results of repeat measurements may vary by ±0.2% while the results are reproducible to ±0.5%. In the current study, repeatability was found to be even lower at around ±0.1% for measurements in the lab. Samples measured with the Rhopoint IQ-S included not only different PV modules, but also façade materials as well as existing building façades in Munich and Torgau, Germany. Each sample was measured between 3 to 5 times on different positions and the average taken. A measurement position dependent variation of up to ±0.3 GU was found for the matt appearing PV modules, while measurement variations of up to ±4 GU were found for semi-glossy PV modules.

2.2 Bidirectional reflectance distribution function (BRDF)

While an assessment of the glossiness of a surface can provide an indication of risk of glare in specular direction, it cannot provide information on the intensity of reflected light outside the specular direction. The measurement of the bidirectional reflectance distribution function (BRDF) provides a method to assess reflection into all directions other than, but also including the specular direction [15]. With this method, light is directed at a particular angle onto the sample and reflection measured at a range of reflection angles using a gonioreflectometer. This equipment allows the precise positioning of both light source and detector. Measurements presented in this study were performed in two independent labs. The sample under investigation was the BIPV module SKALA Green from the manufacturer AVANCIS. The BRDF measurement was performed in the first lab using a 75W Hamamatsu Xenon lamp as light source. Its unpolarized broadband spectrum is directed onto the sample and the reflected light detected by the spectrometer from Instrument Systems, CAS 140CT. The sensitivity of the detector ranges from 380nm to 1100nm. Reflected light is

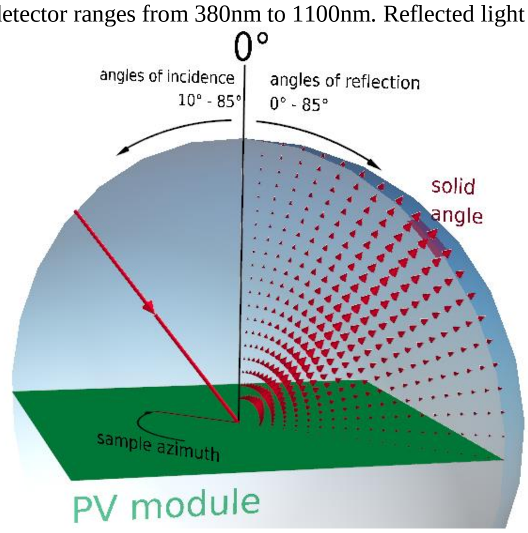


**Figure 2**. Geometry for 2D BRDF measurements: angles of incidence ranging from 10 to 85° while reflection is measured at angles ranging from 0 to 85° (for lab 1). The measurement is performed in plane with the light incidence.

measured spectrally resolved within this range of wavelengths as radiance through the solid angle, i.e. W/m²sr. Incident light is given as the irradiance in W/m². BRDF results are defined as the ratio of scattered radiance to irradiance. Consequently, BRDF results are quoted as unit per solid angle, i.e. $sr^{-1}$. The second lab applied the same principle, but used a monochromatic light source at a wavelength of 638nm. In this setup, small format samples of AVANCIS SKALA Green, Grey and Black were measured, showing different appearances of glossiness.

In the present study, incident angles are varied from 10° to 85° in 5° steps, while scattered light is detected at angles ranging from 0° to 85° in 1° steps in plane with light incidence for the first lab and from -85° to 85° with the same step size in the second lab (see Figure 2 for an illustration of the measurement setup). The setup therefore allows measurement of reflection not only in specular direction (i.e. where incident angle equals reflection angle), but also in scattering directions. The direction into which light is reflected most strongly can thus be determined.

### 2.3 Luminance and glare

In a scientific report concerning glare [16] the German commission on radiation protection defines absolute glare to occur when the incoming light source is so strong that the human eye can no longer adapt to this luminance and the person is blinded. For glare assessments a threshold of $1.6\times10^5$ cd/m² is typically applied as the critical luminance at which this occurs. Luminance levels of $10^4$ cd/m² can produce similar effects under certain luminance contrasts. Other countries, while being equally concerned with the phenomenon of glare, have not included a threshold value of luminance for glare [17]. The appropriateness of available criteria for the assessment for glare have been questioned by a previous study [18]. However, since the threshold value reported in [16] is used frequently in glare assessments as well as the cited publications on glare, it will also serve as a reference point for this study.

Luminance is defined as the radiation per area in the visible wavelengths considering the sensitivity of the human eye as well as the solid angle over which the radiation is measured. It is given in units of candela/m² which are equivalent to the luminous flux (in lumen/m²) per steradian.

The sensitivity of the human eye is expressed by the spectral luminous efficiency function, V(λ). This shifts slightly depending on the surrounding brightness. For daylight vision the photopic spectral luminous efficiency function should be used (see Figure 3).

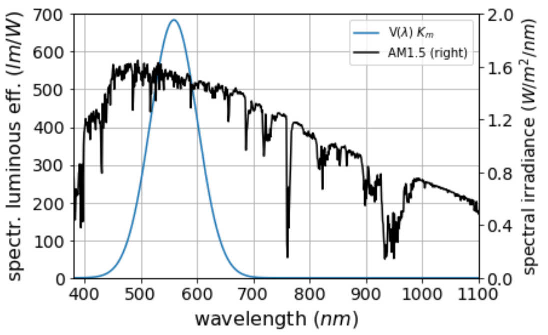


**Figure 3.** AM1.5 spectrum (in black) and the photopic spectral luminous efficiency function V(λ) (in blue) used to convert radiometric units, W/m², into photometric units, cd/m².

Irradiance of the Sun, on the other hand, is generally given in units of W/m² (see Figure 3 for the AM1.5 spectrum of 1000 W/m² [19]). In radiometry, the whole range of optical electromagnetic radiation is considered as opposed to photometry which only considers the spectrum in the visible range.

In order to be able to judge whether reflected radiation may cause glare, a conversion from radiometric to photometric units is required. Conversion into luminous flux $\Phi_V$, i.e. into lm/m², is performed using Equation (1):

$$\Phi_V = K_m \int_\lambda \Phi_{e,\lambda}(\lambda) V(\lambda) d\lambda \quad (1)$$

where $K_m$ is the maximum luminous efficiency for photopic vision (683 lm/W at 555nm), $\Phi_{e,\lambda}(\lambda)$ is the irradiance in W/m²/nm and $V(\lambda)$ is the unitless photopic spectral luminous efficiency function (Figure 3) [20].

Dividing by the solid angle of the light source results then in luminance in cd/m². For the AM1.5 spectrum and using the solid angle subtended by the Sun on the sky as seen from Earth, this conversion leads to a luminance of the Sun of $1.6\times10^9$ cd/m² during midday on a clear day. Accepting the threshold for glare as stated earlier, only surfaces with a reflection of less than 0.01% would prevent glare at these conditions.

## 3 RESULTS

### 3.1 Specular reflection through gloss measurements

Measured gloss values of various PV modules, conventional façade materials as well as of existing building façades are shown in Figure 4. Results are expressed in gloss units, or GU, a scaling system related to the percentage of light reflected as described in Table I. The angle at which the measurement was performed for each material was chosen according to the definition in Table II.

According to [12], materials with a gloss value below 10 GU are described as “matt”, while materials with a gloss value above 70 GU are considered glossy. Materials with gloss values in between these boundaries are considered “semi-glossy”. The majority of passive façade materials and façades measured falls into the “semi-glossy” category. Conventional façade materials (yellow in Figure 4) cover the whole range of glossiness with a few materials exhibiting matt properties, while others reflecting light strongly enough that they are categorised as glossy. Roof-top PV modules from different suppliers (orange in Figure 4) all fall into the category of semi-glossy. Our product line AVANCIS SKALA Colour (in green in Figure 4) falls entirely into the “matt” category exhibiting very low gloss values below 10 GU, often even below 5 GU. A notable exception is AVANCIS SKALA Black with reflection properties comparable to conventional PV modules. AVANCIS SKALA Colour represent one of the least glossy materials in this study. Only among the measured building façades (shown in blue in Figure 4) can materials be found that reflect even matter than these PV modules, that have been particularly designed for the installation in building façades. Stone façades of prominent old buildings in Munich resulted in very low values. It should be noted, however, that results of historic buildings are likely associated with a large error as placing the measurement equipment onto the macroscopically very rough surface proved to be rather

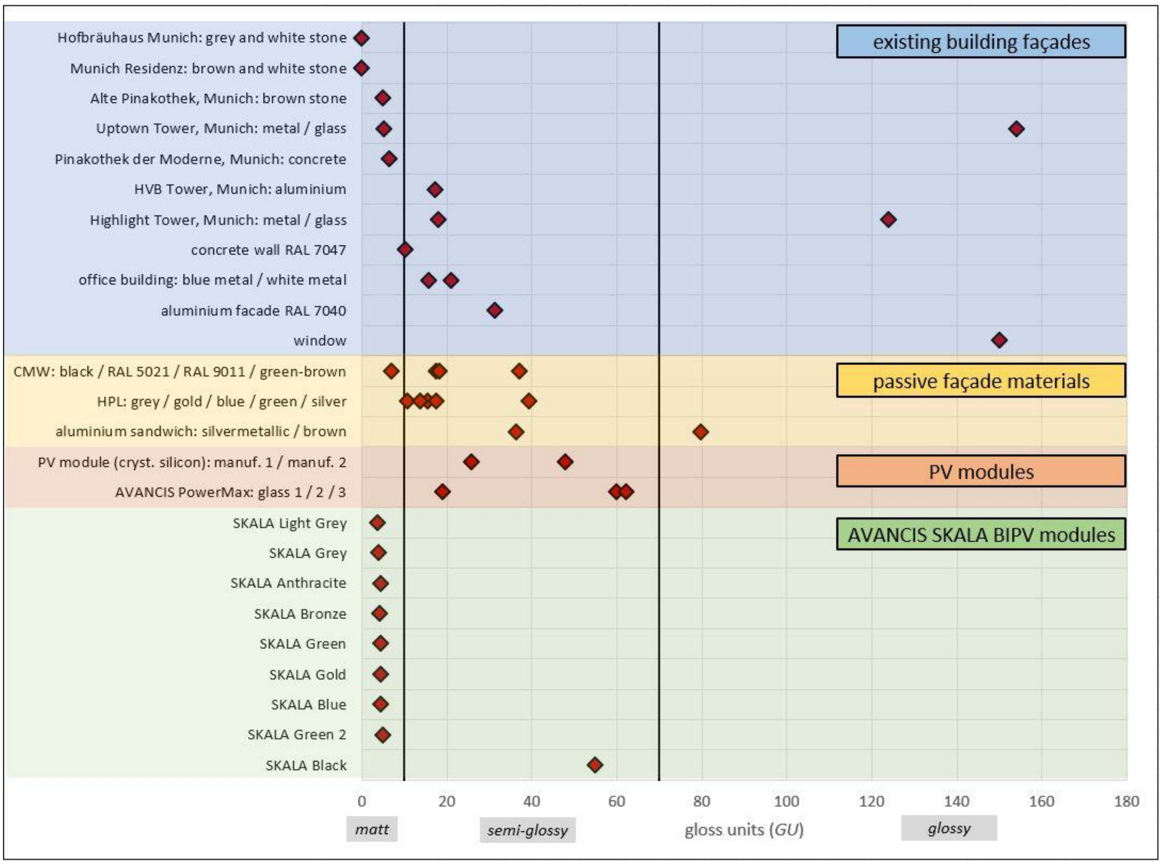


**Figure 4.** Gloss values of PV modules and façade materials as well as already existing building façades. CWM: compressed mineral wool, HPL: high pressure laminate. See subsection 2.1 for details on how data was acquired as well as an estimate of the measurement error of these values.

difficult. Diffuse light entering or leaving the measurement cavity of the equipment may have affected the measurement in these cases.

Interestingly, glass façades of existing buildings have the highest gloss values in this study. Even roof-top PV modules, for which glare assessments are often demanded by concerned stakeholders, do not reach these levels of light reflection in specular direction. Previous studies echo these findings by pointing out that anti-reflective coatings are typically applied to PV module glass surfaces, thus significantly reducing light reflection [21].

Repeating gloss measurements on the very matt BIPV modules SKALA (in green in Figure 4) after three months of outdoor exposure, heavy soiling and extensive cleaning did not show any change in gloss values.

Repeating these measurements again on SKALA modules in wet conditions showed that reflection strongly increases for comparably matt PV modules when the surface is wetted, while this effect was not as strong for more glossy modules or materials. However, once the modules were irradiated with sunlight, they dried within minutes, making these wet conditions practically irrelevant for vertical BIPV installations since sunshine and rain usually do not appear together.

Judging from the measured gloss values, as presented in Figure 4, an increased concern regarding disturbing glare from PV installations in an urban environment appears questionable. Since the light reflection properties of market-typical passive cladding materials lie in the range of those of PV modules, there seems to be a bias assuming an increased risk of glare from PV modules that is, however, not reflected in industry-approved light reflection measurements. If concern is justified, it should rather focus on conventional glass façades. Further, the measured values clearly dissent the still-common practice by some entities conducting glare assessments assuming reflective properties of window glass for PV modules.
Assuming the validity of the threshold for glare as stated in subsection 2.3 as well as reliable measurement values of the applied gloss meter for very low reflection values, none of the considered passive façade materials is free of disturbing glare effects and even concrete and stone façades of existing buildings would pose a potential risk of glare.

3.2 Scattered reflection through BRDF

Light reflection is often described using the 3-component-model which simplifies light reflection into a specular, a haze and a diffuse or Lambertian component [22]. In this model, the strongest intensity is reached in specular direction through the specular component. Less intense light is reflected in the haze component which widens the specular peak. Finally, the diffuse component describes light reflected in all directions at a rather low intensity. As gloss measurements only measure the specular component, a low gloss value may indicate, that a different component in the model is dominating. It is therefore hypothesized that matt samples, such as the BIPV modules SKALA, scatter light at a larger range of angles with a comparatively low intensity compared to glossy samples, such as window glass. Photographs of special façade PV modules as well as roof-top PV modules

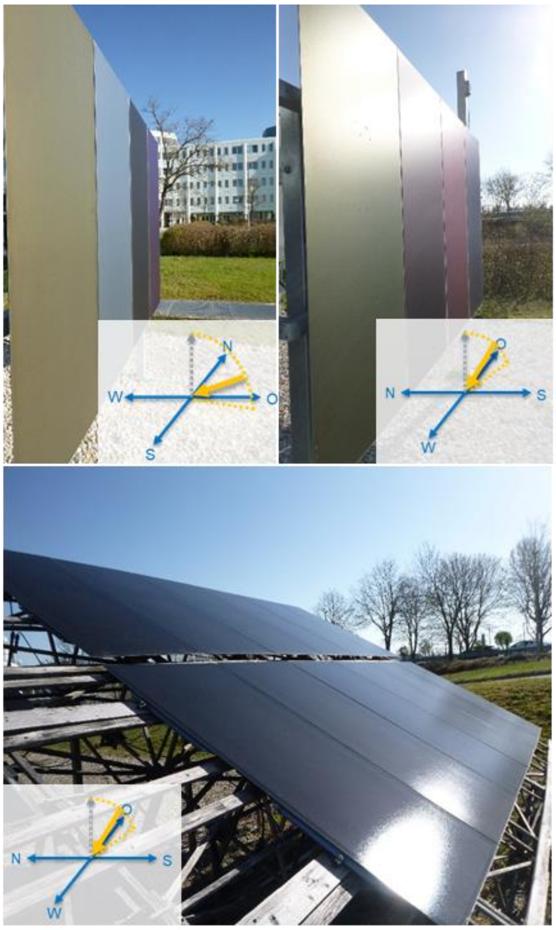


**Figure 5.** Pictures of various BIPV modules AVANCIS SKALA with incident sunlight at small angle to normal direction (top left) and at large angle to the normal (top right). As a comparison, roof-top PV modules AVANCIS PowerMax with incident sunlight at large angle to normal (bottom).

illustrate the visual appearance of matt modules (top) and semi-glossy modules (bottom) (see Figure 5).

Exploring this further, BRDF results extend on gloss measurements by measuring the scattered radiance in the plane of incident light (see Figure *2* in the previous section). Figure *6* illustrates the difference in reflection behaviour for glossy and matt samples. The results show a measurement at an incident angle of 60° at a wavelength of 638nm performed in the second lab described in the experimental setup. In this case, reflection was not only measured in the quadrant opposite to light incidence such as illustrated in Figure *2*, but also in the quadrant of incident light. Negative angles on the x-axis refer to angles in the latter quadrant. Three almost identical curves with an almost non-distinguishable peak in specular direction are shown in grey, green and blue. By comparison, a fourth curve in black shows a prominent peak with its maximum in specular direction, i.e. at a measurement angle of roughly 60°. Photographs of the illuminated samples (below graph in Figure *6*) confirm that the sample with the strong specular peak has a semi-glossy appearance and represents a small sample of a roof-top PV module, while the curves with a rather smooth gradient correspond to samples equivalent to BIPV modules AVANCIS SKALA Colour. As hypothesized from gloss measurements, these results confirm that a semi-glossy sample mainly reflects

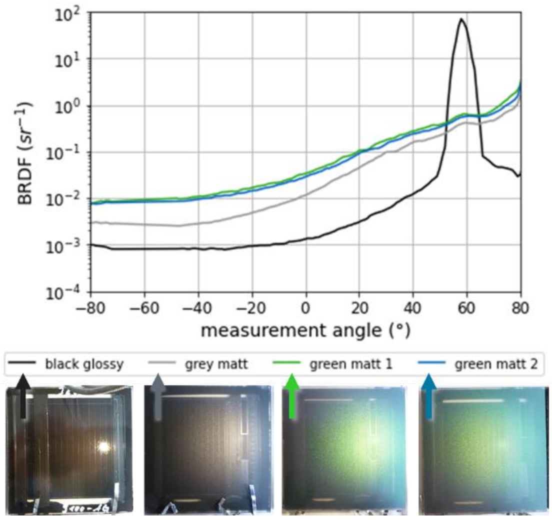


**Figure 6.** BRDF results at 638nm incident light wavelength and 60° incident angle for four different samples. The black curve represents the measurement on a module stack equivalent to the PV module AVANCIS PowerMax and the three other curves the measurement on modules stacks equivalent to the BIPV modules AVANCIS SKALA Colour (Grey, Green 1 and Green 2).

light into specular direction (hence the strong peak for the curve in black) while matt samples scatter the light over a range of angles (hence the lack of a clear peak for grey, green and blue curves). In fact, the graph shows, that the matt samples reflect most strongly at the largest angles. The maximum reflection in this case does not occur in specular direction, but at angles above 80°. The maximum values of the matt samples are, however, still lower by two orders of magnitude compared to the semi-glossy module. For any of the curves, backscattered light, i.e. at negative measurement angles, is of rather low intensity and the analysis in the following will therefore concentrate on the reflection measured at positive measurement angles.

For further tests, a commercially available BIPV module AVANCIS SKALA Green (corresponding to ‘green matt 1’ in Figure *6*) was investigated with BRDF in the first lab as described in the experimental setup. In Figure *7*, BRDF results are shown for different illumination angles, from 10° to 80° in 10° steps. These results confirm that reflection is stronger at large angles. The combination of large incident and large measurement angle produced the strongest light reflection (see grey

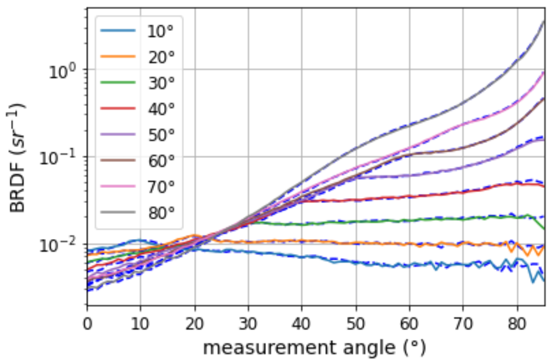


**Figure 7.** BRDF results for AVANCIS SKALA Green for two different sample orientations at incident angles ranging from 10° to 80° in 10° steps. Dashed lines represent the same measurements with the sample azimuth turned by 90° (see Figure 2).

curve in Figure *7*). Starting from an incident angle of 40°, the maximum is pushed to measurement angles above 80°. Increasing the incident angle increases the slope of the curve and the absolute value of the maximum. Additionally, Figure *7* shows two sets of BRDF results for the same sample, but with different sample azimuths, i.e. with the sample rotated around the normal direction (see Figure *2*). Results are identical for both sample orientations. An isotropic module surface can be assumed. In a vertical installation, turning the module orientation around the normal direction of the module would not change reflection behaviour.

## 4 ESTIMATING REFLECTED LUMINANCE

Gloss measurements have shown that our BIPV modules SKALA Colour reflect light rather weakly compared to other materials and PV modules. It is therefore expected that the risk of glare for these modules remains rather low. BRDF measurements have shown that the most severe reflection from these very matt PV modules occurs at very large observation angles to the normal, particularly when the sun rays hit the module at large incident angles. It is therefore expected that the risk of glare may only occur at very specific situations and times of the day.

Using the standard spectrum AM1.5 [19] of 1000 W/m² corresponding to the maximum irradiance by the Sun during the day and performing a conversion into luminance based on Equation (1) and multiplying by BRDF results to get reflected intensity, luminance levels at or above $10^5$ cd/m² were reached at incident and reflection angles above 70° only. However, further converting these calculations into percentage reflection and comparing to gloss measurements, revealed an order of magnitude discrepancy between BRDF and gloss values. A similar discrepancy was observed for BRDF measurements conducted at two independent labs on the same type of PV module: The BRDF curves showed very good agreement qualitatively but an observed order-of-magnitude discrepancy in the actual measurement values could not be explained. It was therefore concluded that a quantitative interpretation of BRDF is not appropriate, but that the results give information regarding the relative distribution of light reflection over a range of angles only. In this regard, the curves of both labs matched showing maximum reflection at large incident and reflection angles for the PV module SKALA Green.

Plotting BRDF in specular direction spectrally resolved (see Figure *8*) further confirms increasing reflection with increasing angles, but also shows how the visual impression changes at large angles. While the colour impression is clearly visible at smaller angles with the normal to the module, showing a peak at wavelengths just above 500nm, (i.e. green colour) where the human eye is most sensitive (compare V(λ) in Figure *3*), at large angles the curve flattens, reflecting wavelengths almost equally across the visible spectrum and at a stronger intensity. An observer will therefore experience white light at an intensity an order of magnitude stronger at this angle (compare visual impression in Figure *5*, top panel). Gloss results suggest that up to 2% of incident light is reflected at these large angles. According to the definitions of luminance and glare given in section 2.3 this would result in critical levels of glare at and near the Sun's maximum irradiation, thus at high elevation, when large

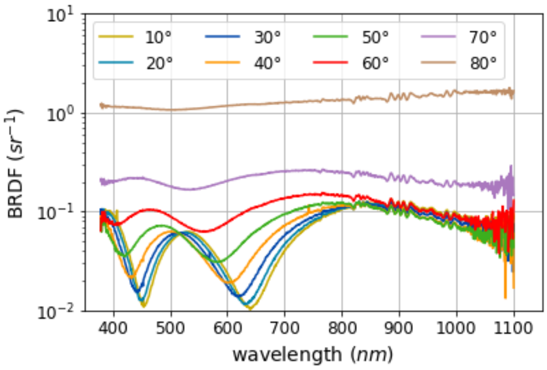


**Figure 8.** Spectrally resolved BRDF results in specular direction, i.e. where the angle of incidence corresponds to the angle of reflection.

reflection angles in-plane with light incidence are directed to the ground and not into the eye of a passer-by.

In fact, measuring luminance directly during a sunny day in August on a south-facing vertical installation of the BIPV modules AVANCIS SKALA, one was not able to detect critical luminance levels at or above $10^5$ cd/m². Even positioning the equipment at a large observation angle near 80° in plane with the Sun at maximum elevation (65° in Munich) did not result in these critical levels. For a module installation at eye level of an observer either looking at the installation in the normal direction of the modules or at angles above 80°, the maximum luminance levels detected reached values of the order $10^3$ cd/m².

## 5 CONCLUSIONS

Since gloss measurements showed that conventional passive façade materials as well as window glass tend to reflect light even stronger than special façade PV modules, an unnecessary discrepancy seems to exists in how appropriate a material is considered for façades, depending on whether they are PV modules or conventional passive materials. The BIPV modules AVANCIS SKALA Colour were among the least reflective materials measured in this study. Closer investigation of light reflection from this kind of modules with BRDF measurements showed that maximum reflection occurs indeed at large measurement and incident angles. This combination of large incident and reflection angles would become relevant to an observer of a south-facing façade installation only in the morning and the evening hours when the Sun's elevation is relatively low. In this scenario the field-of-view of the observer would also include the Sun itself, so that the risk of glare from reflection is considered negligible. In fact, luminance measurements for an observer at a large angle to the normal of a vertical south-facing BIPV installation with AVANCIS SKALA Colour detected luminance levels of only up to $10^3$ cd/m² throughout a clear summer day in Munich, Germany, not reaching critical levels for glare.

The study showed further that material properties of different glass surfaces (window glass and PV front glass of different module types and manufacturers) can affect light reflection significantly, so that basing an analysis of light reflection from PV modules on window glass properties will significantly and unnecessarily overestimate the risk of glare.

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