Certification of solar glass for PV application

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ABSTRACT
The SPF solar glass certification was developed in 2002 to guarantee the quality of glazing for use as a transparent cover for solar thermal collectors. More than 200 glass types from leading manufacturers have been measured and certified to date. Despite the certification having been explicitly developed for solar thermal applications, it became widely used in the PV module industry, even though the results are not transferable and may lead to erroneous conclusions in some cases. In 2012 the certification was therefore adapted to the needs of the PV industry, and a dedicated PV solar glass certification has since been available. This paper explains the fundamentals of the certification process, which consists of three performance characterizations: 1) transmissivity, 2) incident angle modifier (IAM), and 3) UV degradation. Results are discussed for different representative glass types, including float glass, anti-reflective-coated glass and rolled glass with different structures. Furthermore, the performance of these glass types when used as covers of crystalline silicon PV modules is compared. The examples presented also highlight the advantages of the adapted characterization methods compared with standard glass measurements.

Introduction

The performance of a PV module depends on, among other things, the optical properties of the glass used for the cover. Recent developments – such as anti-reflective (AR) coatings or heavily structured glasses – directly address the optical performance of the glass cover in order to increase the module efficiency and decrease the relative cost of solar electricity. Assessing and quantifying the effect that the glass cover has on the yield of an entire module is a laborious task. Nevertheless, because cost pressure on manufacturers has increased in recent years, this information is very important in accurately determining estimates relating performance to price.

The Institute for Solar Technology (SPF) has a long tradition in testing and certification of different materials and systems for the solar industry. In 2002 SPF introduced a certification for solar glass used in solar thermal applications in which the glass is the front cover of a solar thermal collector. Since then, more than 200 glasses from leading glass manufacturers have been certified. Because of the lack of any other certification for solar glass it also became widely used in the PV industry. The certificates and corresponding test results are published on the internet (www.spf.ch). As this certification scheme was specially tailored to solar thermal applications, its results can lead to misinterpretations when directly transferred to PV applications.

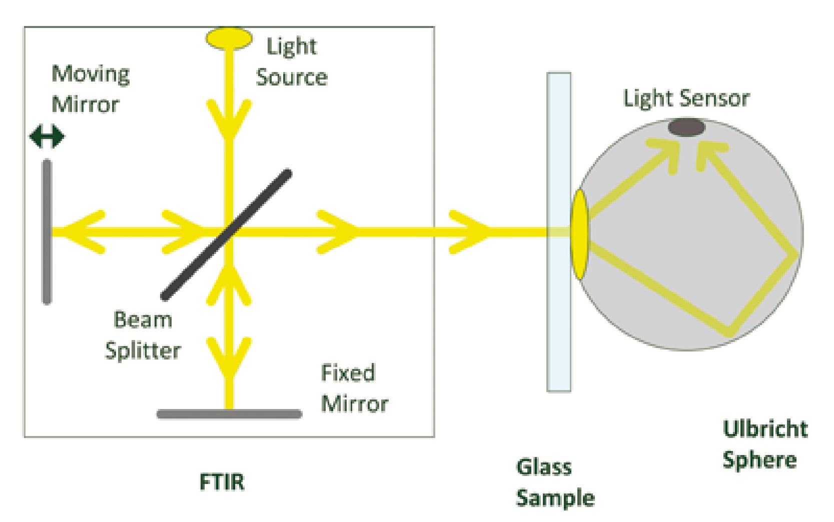

Figure 1. Measurement of direct/hemispherical transmittance using an integrating sphere. The diagram shows a Fourier transform spectrometer (FTIR), but other types of spectrometer can also be combined with integrating spheres.

> "A new certification procedure adapted specifically to the application of glass as the cover sheet for a module with crystalline silicon cells was introduced by SPF in 2012."

The characterization process was adjusted during a project funded by the Swiss Federal Office of Energy, and a new certification procedure adapted specifically to the application of glass as the cover sheet for a module with crystalline silicon cells was introduced by SPF in 2012. The result of the certification is the so-called *glass efficiency factor*, which is intended to be directly proportional to the influence that the glass has on the performance of a typical PV plant in central Europe. The certificate takes into account only the optical properties of a particular glass.

Fundamentals of optical glass measurement

The common method of assessing the performance of solar glass is to measure the direct/hemispherical spectral transmittance; for such measurements, spectrometers combined with integrating spheres (Ulbricht spheres) are used. Fig. 1 shows an example of such a set-up, in which the measured glass is situated in an air environment. The SPF optical laboratory set-up, with an integrating sphere and a sample glass in front, is shown in Fig. 2.

For PV applications a weighted integration of the transmittance spectrum by a typical solar spectrum and a typical sensitivity of the desired cell technology can provide a single value of the 'overall transmittance', and is referred to as the transmissivity. Conventional untreated solar glass achieves a weighted transmittance in the region of 91%, with around 4% being reflected at the front side and around 4% at the back because of the difference in the refraction index of glass (n_{glass} ≈ 1.5) and air (n_{air} ≈ 1) (see Fig. 3). For good solar glass, less than 1% is lost by extinction in the glass body. Multiple reflections also take place internally but only account for about 0.2% of the total transmitted light.

Because of the direct lamination of silicon cells to the back side of the glass, the optical situation for a typical PV module is different from that in the usual air–glass–air set-up, as can be seen in Fig. 4. The matching of the refractive indices of glass and the embedding material (mainly EVA) almost eradicates the reflection at the back side of the glass: for typical values (n_{glass} = 1.5; n_{EVA} = 1.48) the reflection is less than 0.005% and can be neglected. Despite a glass transmissivity of only 91%, measured using standard techniques, around 95% of the incident light reaches the cell in a typical PV module setting. This value can be increased to more than 98% by the use of AR coatings.

The new certification scheme, which will be explained in the next section, introduces a method for correcting the transmittance measurement for the back-side interface reflection and quantifies the amount of light transmitted to the cell. In a typical cell there are also reflections from the cell, wiring and backsheet, which are to some extent reflected back to the cell at the glass front surface. Since this effect is strongly dependent on the cell and wiring type, it is not taken into account in the certification process. For typical modules (7% reflection, flat untreated glass), the magnitude of the effect is of the order of 0.3%, and this is now decreasing as a result of ongoing cell improvements or the use of AR coatings.

The above-described inconsistency between the usual measurement method and a typical module setting also exists in the assessment of the angle-dependent transmittance, usually characterized by the incident angle modifier (IAM). The next section also describes a new method for the assessment of the IAM in a typical module setting, without the glass–air back-side interface.

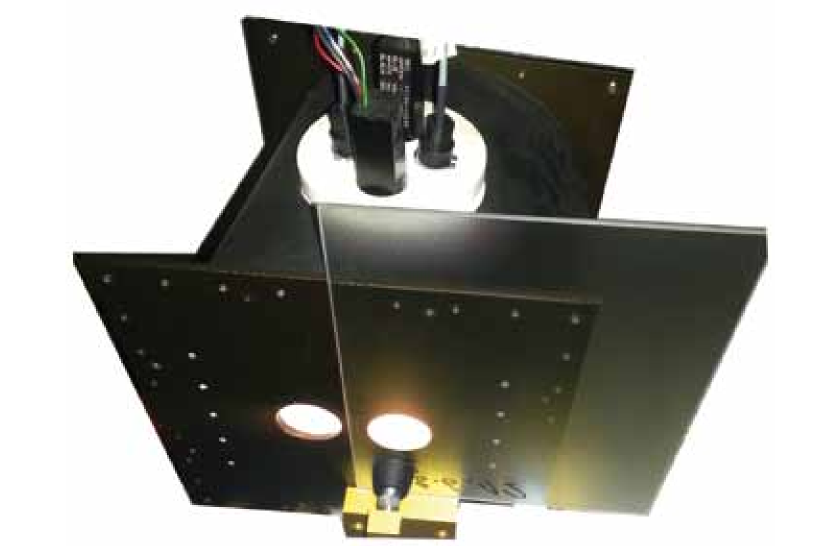

Figure 2. Sample glass in front of an integrating sphere at the SPF optical laboratory – the sphere is inside the black housing. During measurements, the sample glass covers one of the two sphere apertures. Four detectors with different wavelength sensitivities are fixed on the top of the sphere.

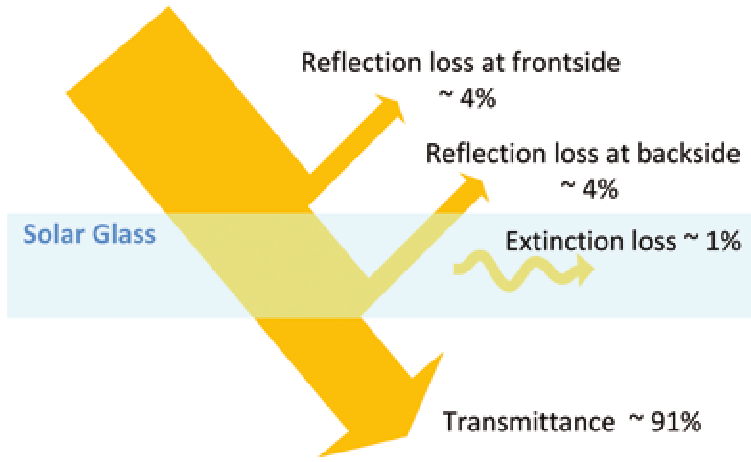

Figure 3. Optical losses of solar glass in an air–glass–air set-up.

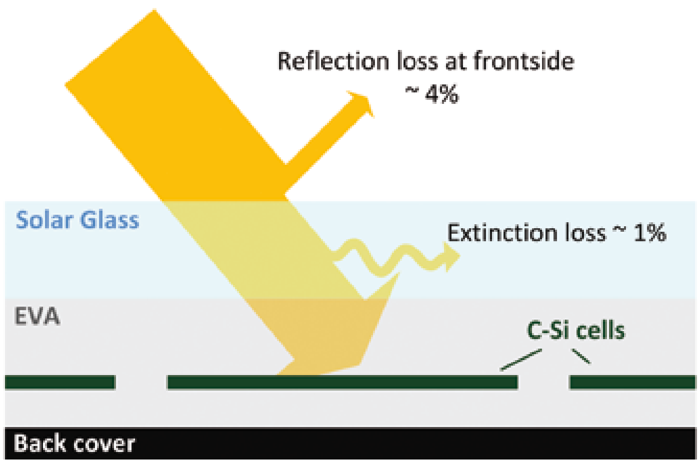

Figure 4. Simplified model of the optical losses caused by the glass in a PV module set-up.

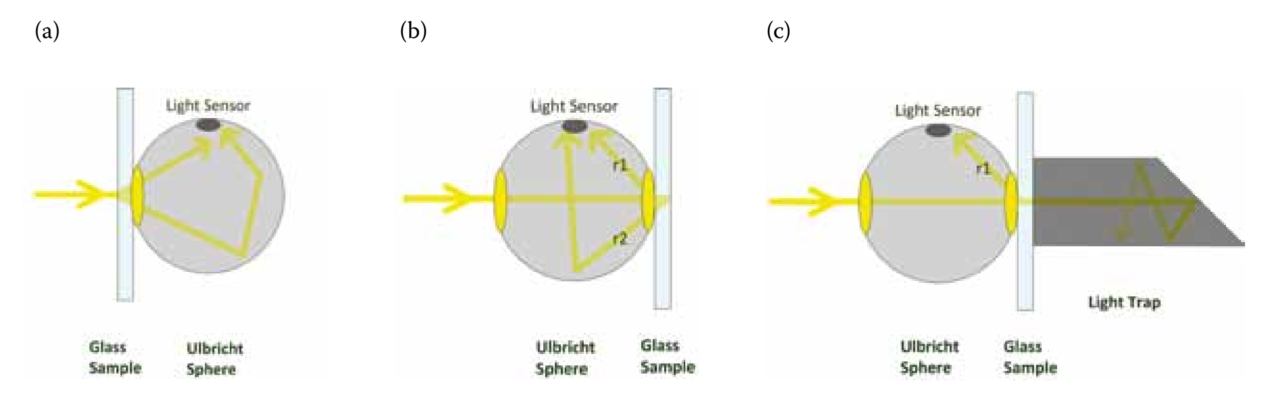

Figure 5. Calculation of the BIC transmittance from three measurements: (a) transmittance measurement in air; (b) reflectance measurement in air; (c) reflectance measurement with a light trap.

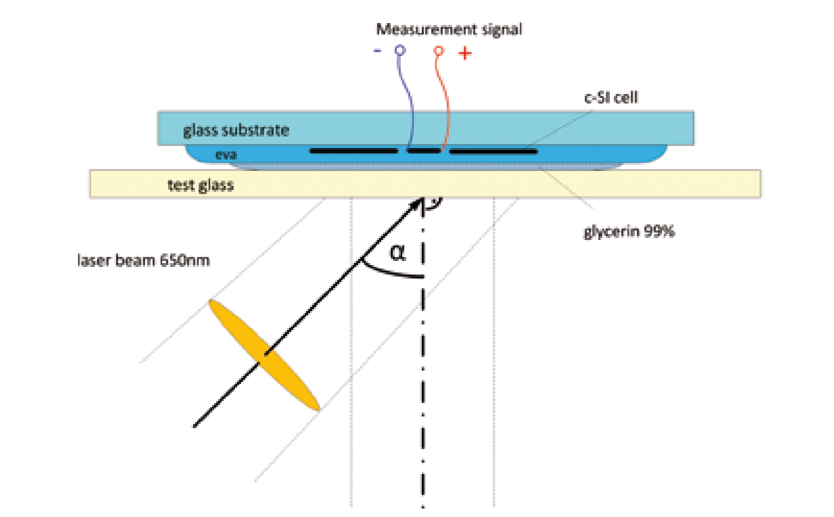

Figure 6. Schematic of the equipment for measuring the IAM of a sample glass. To eliminate the reflection from the back side, the glass is optically coupled to the detector using liquid glycerin.

"The most important performance characteristic of a glass cover sheet is its transmissivity."

Glass certification scheme for PV application

The aim of condensing all assessed optical performance characteristics of a solar glass into a single value has led to the definition of the PV glass efficiency factor η_{GLPV}:

$$\eta_{GL,PV} = F_{\tau,PV} \cdot F_{IAM,PV} \cdot F_{UV,PV} \quad (1)$$

This quantity is the product of three performance factors (assessed using different methods): the transmittance factor ($F_{\tau,PV}$), the incident angle modifier factor ($F_{IAM,PV}$) and the ultraviolet (UV) degradation factor ($F_{UV,PV}$). These three factors will be explained in the following sections. The idea of these performance factors is to express the influence of a performance characteristic by a single number, which is proportional to the influence of the glass on the annual performance of a defined reference system. This system consists of crystalline silicon PV modules located at Rapperswil in Switzerland (typical central-European climate, coordinates: longitude = 8.82° E, latitude = 47.23° N), with an inclination angle of 30 degrees and facing south. It has been shown in the literature that the results are not very sensitive to changes in the reference system and, with good agreement, the results are transferable to other locations [1].

Transmittance factor $F_{\tau,PV}$

The most important performance characteristic of a glass cover sheet is its transmissivity, which is mainly influenced by the content and oxidation state of iron ions and by the quality of an AR coating. As mentioned in the introduction, the transmittance in an air–glass–air setting is different from that in a PV module, so for this reason the 'back-side interface corrected (BIC) transmittance' has been defined. This consists of the fraction of incident light passing the glass in a module setting, when a perfect match of glass and encapsulation material is assumed.

The BIC transmittance cannot be measured directly, but is calculated from three different measurements: 1) common total transmittance measurement in air; 2) total reflectance measurement in air; and 3) reflectance measurement where the reflection at the back side of the glass is eliminated by a light trap (Fig. 5). A more detailed description of the model for the assessment is given in Omlin, Ruesch & Brunold [2], where multiple reflections within the glass are also taken into account. The transmittance factor is calculated by a weighting of the BIC transmittance spectrum by a typical solar spectrum AM 1.5 [3] and by the sensitivity of crystalline solar cells [4].

Incident angle modifier factor $F_{IAM,PV}$

For the performance of a solar plant, it is not only the module's efficiency for direct normal incident light that is important, but also its performance for light hitting at several acute incidence angles. The IAM describes the change in performance for different incidence angles relative to normal incidence angles. In the case of a PV module, the IAM mainly depends on the glass front side (refractive index, coating and structure).

A measurement set-up has been developed to determine the IAM (at angles of 30, 40, 50, 60 and 70 degrees relative to normal incidence) of a sample glass in a PV module setting (Fig. 6), which consists of a c-Si measurement cell (from a leading manufacturer) that has been encapsulated in EVA, where only a small area (20mm × 20mm) in the centre of the cell is active and electrically isolated from the rest. The sample glass can be optically coupled to the test cell using liquid glycerin with a refractive index matched to the EVA used. The cell is illuminated from different angles by a homogeneous collimated laser beam over an area that is much larger than the active area in order to counteract border effects. It was demonstrated that this monochromatic light of 650nm was representative of the entire spectral range encountered in practice [1].

To eliminate the effects of the cell used, the measurement of a sample glass is always compared with a reference measurement of the complete set-up without a coupled glass. Weighting factors are introduced in order to quantify the influence of a measured glass IAM to the reference solar plant (Rapperswil, Switzerland, 30-degree inclination, south orientated) and condense all measured angles into one single value – the incident angle modifier factor $F_{\mathrm{IAM,PV}}$. Values of the weighting factors and the formula for the calculation are given in Omlin, Ruesch & Brunold [2]; the derivation of the factors and a sensitivity analysis are given in Ruesch, Omlin & Brunold [1].

UV degradation factor $F_{\mathrm{UV,PV}}$

UV radiation can change the oxidation state of metal ions in the glass bulk or can affect the AR coating. Both effects have a direct influence on the transmittance of a solar glass, so for that reason an accelerated UV degradation test was introduced. A sample glass is exposed for 250 hours to a dose of $80\mathrm{kWh/m^2}$ of UVA and $3\mathrm{kWh/m^2}$ of UVB, which corresponds to an annual load in central Europe. After this UV exposure, the change in performance is measured and condensed into a single factor – the UV degradation factor $F_{\mathrm{UV,PV}}$. Full details of the calculation of this factor are given in Omlin, Ruesch & Brunold [2].

Certification

A classification system was introduced in order to increase the comprehensiveness of the certificate for end users. Solar glasses are split into two groups: group P (Table 1), for untreated glass; and group R (Table 2), for single-sided AR-treated glass. A finely graded sub-classification of these groups is also made, depending on the glass efficiency factor. If the glass does not achieve a specific value, it is no longer classified as solar glass. All certified glasses are published on the SPF website (www.spf.ch).

Results

The SPF PV solar glass certification was introduced in 2012, and already more than 25 glass types have been certified and published, all of them achieving a first-class rating. In order to illustrate a few details of the three performance factors, as well as highlight some differences between standard methods of measurement and those of the adapted certification scheme, a selection of different typical types of glass was examined:

1. Thin float glass.
2. 'Thick' float glass (5mm) with iron contamination.
3. Lightly structured glass.
4. Same as 3, but with an AR coating.

5/6. Two glass types having a structured surface (prismatic).

Table 3 presents a summary of the different glass types measured: the results from the PV certification scheme (right columns) are compared with the results from the conventional solar thermal (TH) certification scheme (left columns). One major difference is that the PV transmittance factors are about 4% higher than the TH transmittance factors based on a conventional measurement in air. Another major difference lies in the IAM factors of heavily structured glasses. The different prismatic structures of glass nos. 5 and 6 have a negative influence on the conventional TH IAM factor measured in an air–glass–air setting. On the other hand, the IAM factors for these two glasses in the PV case (with no reflection at the glass back side) is slightly greater than unity, which means that their efficiencies at elevated incidence angles are slightly higher than that of the reference cell only (flat EVA front surface). Some of these effects will be explained in more detail in the

Class	Classification criteria				
P1			$\eta_{GL,PV}$	≥	0.940
P2	0.940	>	$\eta_{GL,PV}$	≥	0.925
P3	0.925	>	$\eta_{GL,PV}$	≥	0.910
P4	0.910	>	$\eta_{GL,PV}$	≥	0.890
Non-solar glass	0.890	>	$\eta_{GL,PV}$		

Table 1. Classification of untreated glass.

Class	Classification criteria				
R1			$\eta_{GL,PV}$	≥	0.980
R2	0.980	>	$\eta_{GL,PV}$	≥	0.965
R3	0.965	>	$\eta_{GL,PV}$	≥	0.950
R4	0.950	>	$\eta_{GL,PV}$	≥	0.925
Non-solar glass	0.925	>	$\eta_{GL,PV}$		

Table 2. Classification of single-sided AR-treated glass.

No.	Surface structure	Thickness [mm]	$\eta_{GL,TH}$	$F_{\tau,TH}$	$F_{IAM,TH}$	$F_{UV,TH}$	Class	$\eta_{GL,PV}$	$F_{\tau,PV}$	$F_{IAM,PV}$	$F_{UV,PV}$	Class
1	Flat, thin	3.2	0.906	0.909	0.997	1.000	U1	0.943	0.944	0.999	1.000	P1
2	Flat, thick	5	0.886	0.888	0.997	1.001	U2	0.924	0.928	0.995	1.001	P3
3	Light structure	3.2	0.911	0.916	0.996	0.999	U1	0.953	0.955	0.999	0.999	P1
4	Light structure, AR	3.2	0.942	0.940	1.002	1.000	Y1	0.995	0.985	1.010	1.000	R1
5	Prismatic structure 1	3.2	0.852	0.914	0.932	1.000	U4	0.954	0.952	1.002	1.000	P1
6	Prismatic structure 2	3.2	0.884	0.915	0.966	1.000	U3	0.957	0.954	1.003	1.000	P1

Table 3. Examples of glasses with different surfaces.

next section, by showing real measured data of the individual performance characteristics.

Transmittance

In Fig. 7 the BIC transmittance spectrum of a typical solar glass (no. 3) is compared with the conventional transmittance spectrum measured in air. As explained above, the reflectance in air and the reflectance spectrum with an optically coupled light trap have to be measured as well; both spectra are also plotted in Fig. 7. Within the important range of 0.4–1µm, as indicated by the weighting spectrum (C-Si@AM1.5), the extinction in the glass body is small. For this reason, the difference between BIC transmittance and conventional transmittance consists mainly of the reflectance at the back side, which is also the difference between the reflectance in air and the reflectance with a light trap.

To accurately calculate the BIC transmittance, both the extinction in the glass body and the multiple reflections between the glass surfaces are taken into account. The effect of extinction can be seen in the spectral region just above 0.3µm, where the BIC transmittance is higher than the conventional transmittance even though the reflectance in air approximates the reflectance with a light trap.

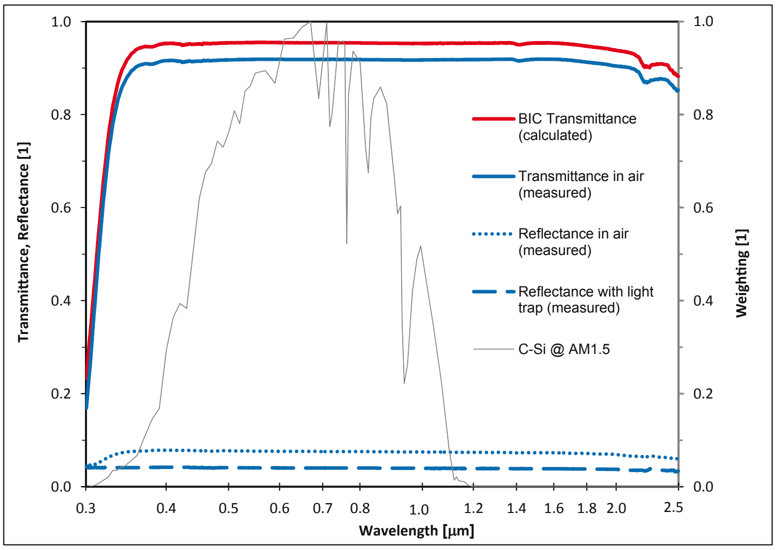

Figure 7. Calculation of the BIC transmittance spectrum from three direct measurements: transmittance spectrum in air, reflectance in air, and reflectance with an optically coupled light trap. As indicated by the weighting spectrum (C-Si @ AM 1.5), it is mainly the transmittance in the range 0.4µm to 1µm that is of importance.

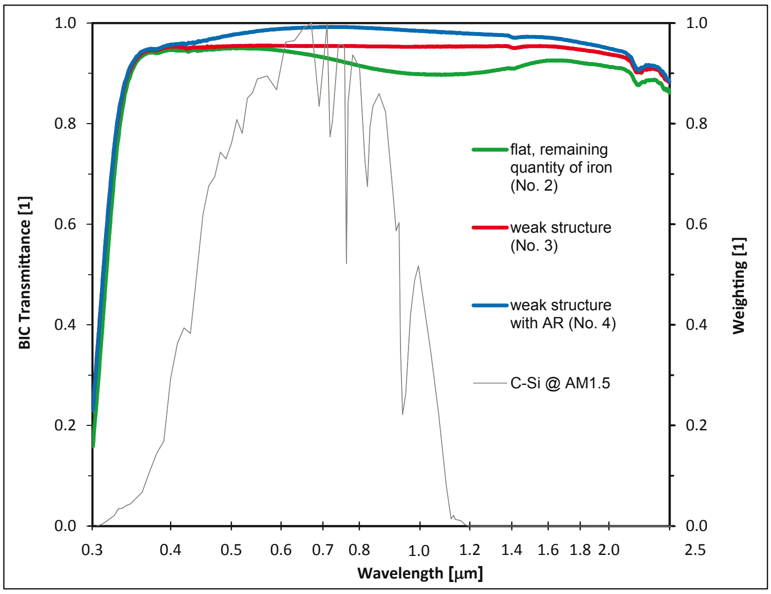

Figure 8. Comparison of the BIC transmittance spectra of a typical solar glass (no. 3), an AR-coated glass (no. 4) and a solar glass with iron contamination (no. 2).

> "To accurately calculate the BIC transmittance, both the extinction in the glass body and the multiple reflections between the glass surfaces are taken into account."

Fig. 8 shows a comparison of the BIC transmittance spectrum of the typical solar glass (no. 3) with the spectra of the AR-coated glass (no. 4) and the glass with iron contamination (no. 2). The effect of the AR coating is tailored to the sensitivity of crystalline silicon cells. The BIC transmittance spectrum reaches its highest level (just less than one) at the centre wavelength of the weighting spectrum (C-Si@AM1.5) at ~0.65µm. The good matching of the AR coating to the cell sensitivity results in the high value of the weighted transmittance ($F_{\tau,PV}$) of 0.985 for glass no. 4: this means that only 1.5% of the usable incident solar light is lost by reflection or extinction caused by the glass, which is a very good value.

On the other hand, the spectrum of glass no. 2 shows a wide extinction band centred around ~1µm, which is typical for Fe^{2+} ions [5]. This extinction affects the sensitivity range of crystalline silicon cells and therefore has a negative influence on the PV transmittance factor ($F_{\tau,PV}$): for the example given (glass no. 2), it is reduced to 0.924 (Table 3).

IAM

Figs. 9, 10 and 11 show the IAM measurements for three glass types: a thin float glass (no. 1), an AR-coated glass (no. 3) and a glass with a prism-like structured surface (no. 6). For each case, the IAM measurement for the PV application (glass optically coupled to the detector) is compared with a conventional IAM measurement in air. The huge difference resulting from the reflection at the back side of the glass in the conventional case can be seen from the difference in the chosen references. In the conventional case, the theoretical value for a flat glass with a front and a back side is used (as reported by the French physicist and engineer Augustin-Jean Fresnel). In the PV case, a measurement of the bare detector without glass serves as the reference, which closely matches the theoretical value of a single glass front surface [1]. As seen in Fig. 9, in the case of a flat solar glass (no. 1) the measured curves almost reach the associated reference curves, resulting in IAM factors close to unity (0.997 for TH and 0.999 for PV).

The measured IAM values of an AR-coated glass (no. 4) have been plotted in Fig. 10. For both the thermal and PV cases, the curves are slightly higher than the reference curves, resulting in IAM factors greater than unity (1.002 for TH and 1.010 for PV). This means that an AR coating increases the electricity production not only by the increase in normal transmittance, but also by a better performance at high incidence angles. For the given example glass and the above-described reference solar plant, the better IAM performance as a result of the AR coating leads to an additional electricity production of ~1%.

A major difference is observed in Fig. 11 for glass no. 6, with the heavily structured surface (prism structure), which leads to low IAM values in the conventional case. On the other hand, the same prism structure has a positive effect on the IAM behaviour in the PV case. This inconsistency results in a serious misjudgement when a conventional glass-in-air measurement is used for the assessment of glass quality in the PV industry.

UV degradation

Most types of modern solar glass do not exhibit any UV-induced degradation and therefore all the sample glasses (from Table 3) indicate a UV degradation factor close to unity. An interesting effect, however, is observed for the glass with iron contamination (no. 2). As can be seen in Fig. 12 the transmittance (in air) at the absorption band of Fe^{2+} around 1μm is slightly higher after 250h of UV exposure. On the other hand, the transmittance is lower in the short-wavelength range of the spectrum, between 0.39 ptm and 0.49 ptm. The increase in extinction matches the absorption band of Fe^{3+} at around 0.379 ptm [5], showing the occurrence of a photo-oxidation from Fe^{2+} to Fe^{3+} during UV exposure. For the transmissivity the two effects counteract each other, but as the Fe^{2+} absorption better matches the cell sensitivity the transmittance is slightly increased for this example (+0.1%). Similar effects can have a negative effect on the glass transmittance, especially when cerium (Ce^{3+}) is involved.

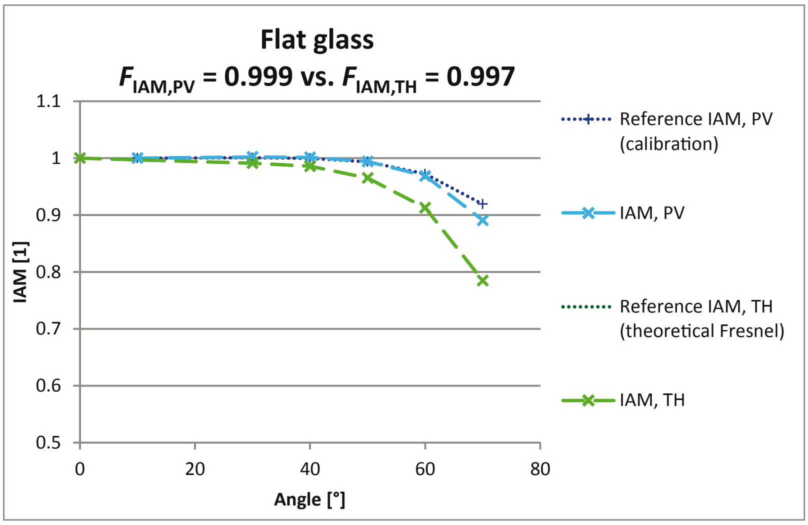

Figure 9. Comparison of conventional and novel PV IAM measurements of a typical flat solar glass (no. 1).

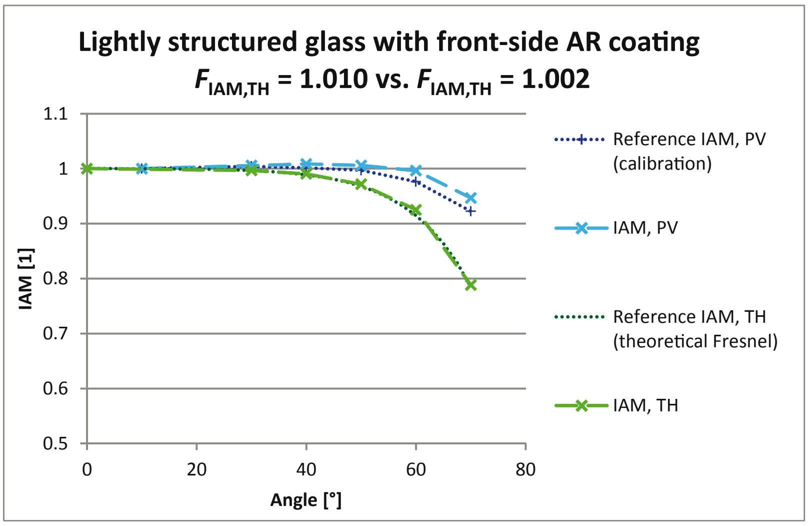

Figure 10. Comparison of conventional and novel PV IAM measurements of an AR-coated solar glass (no. 4).

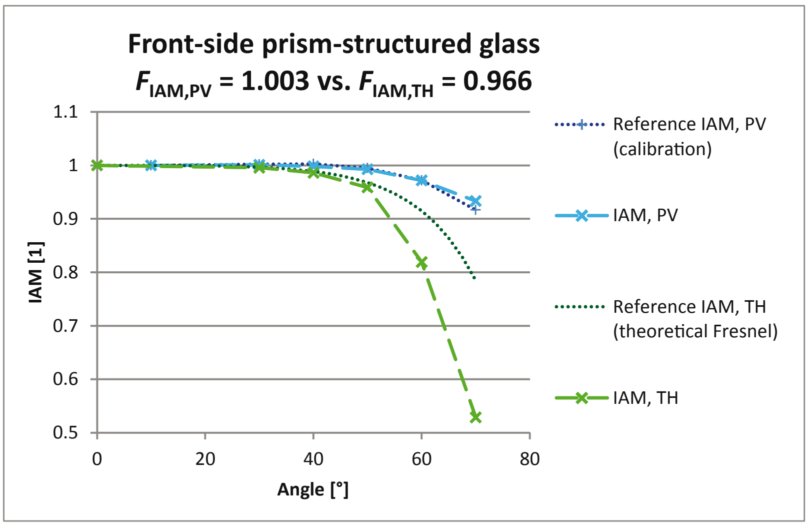

Figure 11. Comparison of conventional and novel PV IAM measurements of a prism-structured solar glass (no. 6).

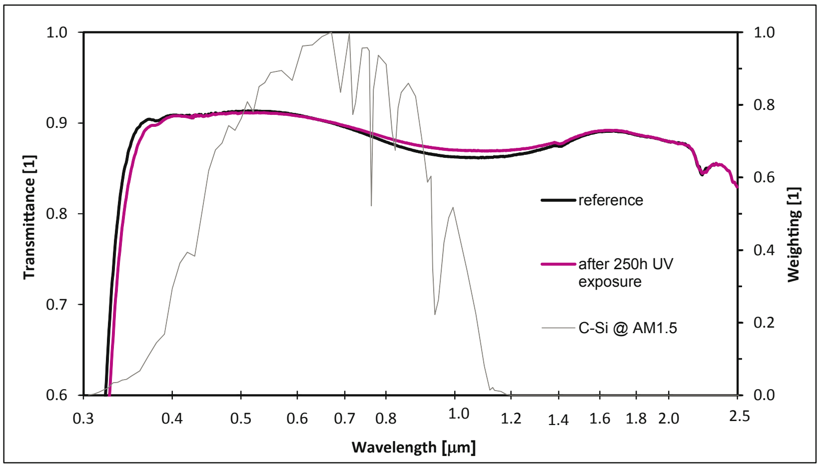

Figure 12. Comparison of the conventional transmittance spectra of a solar glass with iron contamination (no. 2) before and after UV exposition. The change in spectral transmittance is caused by photo-oxidation of Fe^{2+} to Fe^{3+} and leads to a slight increase in the transmissivity.

"Good AR coatings lead to better IAM behaviour and result in an additional annual yield of approximately 1%."

Conclusion

The direct lamination of cells to the back side of the glass cover virtually eliminates the reflection at the glass back side. This effect is not taken into consideration by conventional glass measurements. Instruments and methods for characterizing transmittance as well as IAM by taking account of the eliminated reflection at the glass back side have therefore been introduced. From the analyses of more than 25 certified glasses and additional characteristic glass types, the following conclusions have been drawn:

- Losses caused by reflection and extinction of a good (i.e. low iron) standard glass cover sheet (nos. 1, 3, 5 and 6) only account for about 5% of the annual yield of a typical PV plant in central Europe.
- When good AR coatings are used, only 1.5% of the usable sunlight is lost because of reflection and absorption of the glass.
- Good AR coatings lead to better IAM behaviour and result in an additional annual yield of approximately 1%.
- The influence of the front-side structure on the IAM behaviour of a typical module is minor (which is contrary to the case of thermal collectors). Heavily prism-structured glass even tends to slightly increase the annual yield.
- The transmissivity of today's solar glasses does not tend to decrease because of UV exposure, unlike what was observed to be the case around ten years ago.

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PV Modules

About the Authors

Stefan Brunold is currently the deputy director of SPF-HSR in Switzerland, having previously been the head of the materials and optics department from 1993 to 2003. Prior to that (1990–1992) he worked as a scientist at FhG-ISE, where he focused on transparent insulation materials. Stefan was responsible for the development of the 'SPF Solarglass Certificate' (for solar thermal collectors), which was introduced as a new SPF service to the industry in 2001.

Florian Ruesch graduated in 2006 from EPFL in Switzerland and then worked at PMOD/WRC in Davos. Since 2007 he has been a project leader at SPF-HSR, with a special interest in optics and solar glazing materials. Florian was responsible for the adaptation of the 'SPF Solarglass Certificate' for PV applications in 2012.

Lukas Omlin graduated in 2006 from Bern University of Applied Sciences in Switzerland. Since 2011 he has worked at SPF-HSR as a research engineer and is responsible for optical measurements of glass and other materials in different projects. Lukas was involved in the adaptation of the 'SPF Solarglass Certificate' for PV applications in 2012, for which he designed measurement equipment.

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