Institut für Solartechnik SPF
OST – Ostschweizer Fachhochschule
CH- 8640 Rapperswil
www.spf.ch

Certification of solar glass-PV Photovoltaic modules

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Contents

1 General information

1.1 Introduction

The performance of a photovoltaic (PV) module depends on the optical properties of the cover used. Assessing and quantifying the effect this glass has on the yield of the module is a laborious task, and because cost-pressure on manufacturers has increased over the last years, this information has become ever more important in accurate estimations relating performance to price.

Currently there is no Norm for the testing of solar glass, which is why SPF developed their own certification process, whereby glass can be placed into varying performance-categories based on optical measurements. This classification allows an estimation of the effective module yield in regards to different glass coverings. The SPF-glass-certificate provides thereby a foundation of technical specification for the acquisition and quality assessment of solar glass in the manufacturing of PV modules.

The SPF solar glass certificate encompasses solely optical properties. Aspects of safety, mechanical loading capacity and soiling are explicitly not part of the certificate. All relevant Norms and regulations are to be observed independent of this certificate. In particular, SPF recommends the use of hardened glass meeting the minimum requirements of EN12150.

Due to the differing properties Solar Thermal Collectors and Photovoltaic Modules require of solar glass, there are two respective assessments and certificates:

- Solar glass PV, intended for Photovoltaic modules
- Solar glass ST, intended for Solar Thermal collectors

1.2 Scope

The present certificate is valid for plate-glass (with flat, structured or anti-reflex surfaces) intended for use with crystalline silicon PV modules. In the case that *front* and *back* surfaces differ, it is required that the manufacturer specifies the orientation. Should the glass be intended for *both* orientations a different certificate is required for *each* orientation.

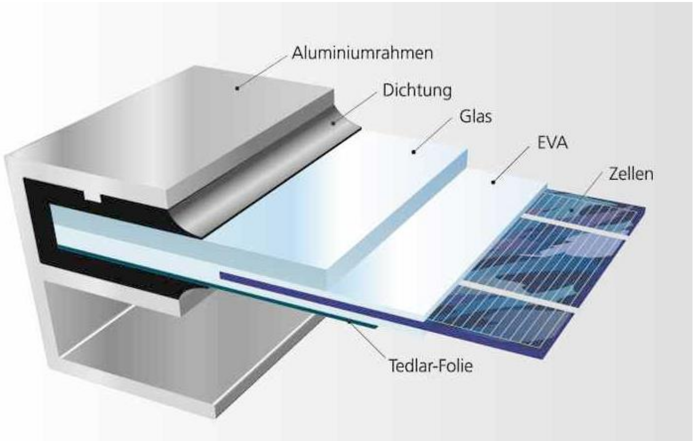

Figure 1: Typical PV module configuration with cells made from crystalline silicon (source: www.renewable-energy-concepts.com)

2 Technical fundamentals

2.1 Performance of solar glass

The optical performance of solar glass intended for use in PV modules can be characterised essentially with three main parameters:

Backside-interface-corrected transmission: This characterises the part of a unilateral incident radiation that is transmitted through the glass to the embedding material at the *back* surface and therewith the amount available for electricity generation in the PV module. When a glass pane is measured in air, the transmission is reduced by extinction in the material body and reflection on both the front and back sides of the pane. In the case of PV modules, there should ideally be next to no reflection at the backside interface (to the embedding material), which is why a measurement of a glass pane in air must be corrected for the backside reflection inherent in the measurement. The unilateral backside-interface-corrected transmission is measured in a "direct-hemispherical" set-up over the spectrum of radiation relevant for PV modules. Typical crystalline solar cells are only sensitive to a limited range of wavelength, therefore the measured transmission spectrum must be weighted for the typical solar spectrum and for the sensitivity of crystalline silicon cells to create a relevant factor. This factor is made up mostly from the refractive index and chemical composition of the glass, as well as any relevant surface effects (anti-reflex coatings). This appraisal is tailored specifically to modules with crystalline silicon cells and is therefore limited in its applicability to other technologies.

Incident angle factor: The annual yield of a PV module depends not only on the transmission of unilateral incident radiation but also that of varying incident angles. This effect is accounted for by the Incident Angle Modifier (IAM) weighting factor. It describes how a measured glass affects the performance of a crystalline silicon solar cell over varying incident angles and whether this might lead to loss or gain in a typical module. In the case of structured surfaces or anti-reflex coatings an improvement in the PV modules' annual yield can be obtained due to their influence at small incident angles.

Aging though photolysis: Photolysis or Solarisation is a discolouration of the glass due to component oxidation resulting from long-term UV exposure and leads to a reduction in transmission. Not accounted for in this test are influences from soiling or degradation due to weather and climate.

2.2 The glass efficiency factor

The PV glass-efficiency-factor $\eta_{GL,PV}$ was defined to combine the performance characteristics of solar glass into a single value. It specifies the influence a glass has on the annual yield of a simulated crystalline silicon PV module reference system positioned in Rapperswil SG, Switzerland (typical middle European climate, coordinates: longitude=-8.82, latitude=47.23), with an inclination angle of 30° facing south.

The glass-efficiency-factor is a product of the above mentioned performance characteristics. Each factor is defined such that they and the overall glass-efficiency-factor $\eta_{GL,PV}$ are proportional to the simulated reference system:

$$\eta_{GL,PV} = F_{\tau,PV} \cdot F_{IAM,PV} \cdot F_{UV,PV} \quad (2.1)$$

For a detailed explanation of each factor refer to Appendix A-C. The effect these factors have on the reference system are calibrated accordingly; as such a PV glass-efficiency-factor of 1 corresponds to a simulation of a fictive glass cover without loss from internal absorption or reflection, having no effect on the incident angle modifier of an embedded crystalline silicon cell and exhibiting no photo-degradation with time.

3 Certification

3.1 General

The rights and duties in the scope of the certification as well as its validity are contractually defined between the Institut für Solartechnik SPF and the manufacturer of the solar glass. The manufacturer can also be represented by distributors or OEM manufacturers. The duties in regard to the rules of the certification are non-negotiable. All certified solar glass types are published on the SPF website (www.spf.ch) – a certification without publication is not possible. Along with the name of manufacturer and contractual representation the important characteristics and classification are displayed.

3.2 Classification and labelling

In the certification procedure a solar glass is categorised into one of two types:

Px: Untreated solar glass
PC: Colored solar glass
Rx: Single-side Anti-Reflex (AR) treated solar glass

Within these two categories a classification is then made based on the efficiency factor. These four classes are shown for each category in the following tables:

Table 1: Classification of untreated glass

P untreated glass					
Class P1			$\eta_{GL,PV}$	≥	0.940
Class P2	0.940	>	$\eta_{GL,PV}$	≥	0.925
Class P3	0.925	>	$\eta_{GL,PV}$	≥	0.910
Class P4	0.910	>	$\eta_{GL,PV}$	≥	0.890
Not solar glass	0.890	>	$\eta_{GL,PV}$		

Table 2: Classification of colored glass

P colored glass					
Class PC	0.000	>	$\eta_{GL,PV}$	≥	1.000

Table 3: Classification of AR treated solar glass

R single-side treated AR glass					
Class R1			$\eta_{GL,PV}$	≥	0.980
Class R2	0.980	>	$\eta_{GL,PV}$	≥	0.965
Class R3	0.965	>	$\eta_{GL,PV}$	≥	0.950
Class R4	0.950	>	$\eta_{GL,PV}$	≥	0.925
Not solar glass	0.925	>	$\eta_{GL,PV}$		

The glass certificate consists thus of the glass category and classification (e.g. **R4** refers to an AR treated glass of the 4th class). Below a certain threshold glass is no longer considered solar glass.

3.3 Certificate identification

For every glass certificate a unique identification is created containing all relevant information. These are listed below with an explanation for the short-forms:

Certifying body	:	SPF
Certificate number	:	Year (2 positions) ● sequential number (3 positions)
Type/Classification	:	see Table 1, 2 and 3

An example of identification:
SPF19●999-R3: Glass with test number 999, tested in 2019, anti-reflex treated glass with the classification 3.

3.4 Validity

The released certificates are valid for three (3) years. It is the duty of the bearer of the certificate to ensure that only the glass certified is distributed with the certificate. In the case where non-certified glass is distributed with an SPF certificate, especially with the knowledge of the certificate bearer, the certificate can be declared invalid and deleted from publication. The bearer of the ticket will be informed and has no claim to reimbursement.

Appendix A: Transmission factor $F_{\tau,PV}$

The transmission factor $F_{\tau,PV}$ quantifies the influence that transmission through the solar glass has on the yield of a typical c-Si PV-module. It is defined by:

$$F_{\tau,PV} = \tau_{cSi} \quad \text{(A.1)}$$

Here, τ_{cSi} is defined as the "direct-hemispheric transmission factor with backside interface correction and c-Si weighting". Weighting consists of accounting for the typical spectral sensitivity of c-Si cells and the well established solar spectrum with air mass 1.5 (AM1.5) of the ISO8945-1.

On the assumption that in the case of c-Si PV modules a glass covering is optically coupled at the backside to an embedding material, an accurate optical assessment must account only for reflective losses on the front side and extinction losses (i.e. inner transmission) in the glass itself. Due to the direct lamination of the c-Si cell to the backside of the glass there are next to no reflection losses at the glass-embedding material interface. The immediately measured transmission spectrum of the glass in air $\tau_{tot}(\lambda)$ - which aside from accounting for the internal transmission loss $t(\lambda)$ also has the reflection losses of the front and backside interface with air ($r_1(\lambda)$ and $r_2(\lambda)$) - must therefore be corrected for the backside interface. These quantities are spectrally dependent and are judged accordingly but are not mentioned in the following notation for reasons of clarity.

On the assumption that multiple reflections are subject to the same scattering, the following model is used:

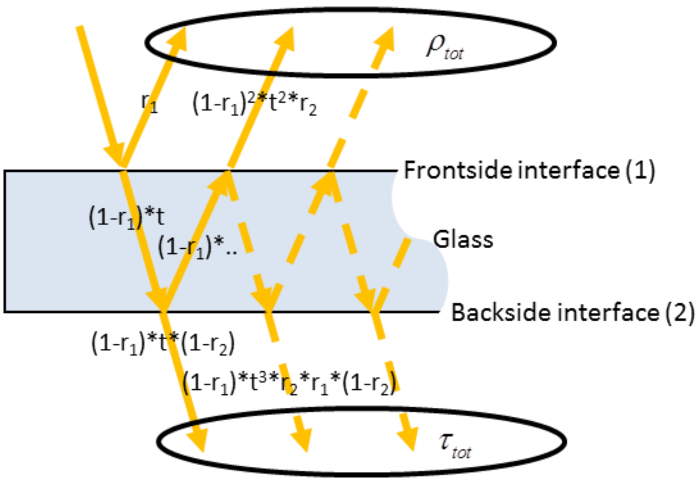

Figure 2: A schematic of the transmitted and reflected scattering occurring in flat glass; made up of reflection at the front (r_1) and backside (r_2) interfaces and inner transmission (t).

As visible in Figure 2 the measureable values for the total direct-hemispheric transmission τ_{tot} and reflection ρ_{tot} are dependent on reflection at the front side r_1, transmission through t and reflection at the back side r_2 of the glass according to:

$$\tau_{tot} = (1-r_1)(1-r_2)t\sum_{n=0}^{\infty} r_1^n r_2^n t^{2n} \quad \text{(A.2)}$$

$$\rho_{tot} = r_1 + (1-r_1)^2 r_2 t^2 \sum_{n=0}^{\infty} r_1^n r_2^n t^{2n} \quad \text{(A.3)}$$

Whereby r_1, r_2 and t are average values of the differently scattered light-rays. The calculation applies under the assumption that the scattering is the same for all multiple reflections, particularly in the case of flat or isotropic scattering surfaces. For anisotropic scattering surfaces this model is not quite correct. For typical types of glass this uncertainty remains significantly below measurement error.

When a *light trap* is coupled to the backside of the glass the respective interface refraction becomes zero (i.e. backside $r_2 = 0$) which, as can be seen in Eq. A.3, leaves a measured direct-hemispheric reflection of $\rho_{tot,Lf} = r_1$. When a light trap is used this direct-hemispheric reflection at interface 1 can be measured directly, as well as ρ_{tot} and τ_{tot}. The remaining unknowns r_2 and t can be found via Eqns. A.2. and A.3 iteratively using the measured values τ_{tot}, ρ_{tot} and $\rho_{tot,Lf}$. The sought value for backside-interface-corrected transmission follows from Eq. A.2 when $r_2 = 0$:

$$\tau_{Kor,G2} = (1 - r_1)t \tag{A.4}$$

The backside-interface-corrected transmission is measured spectrally and weighted with a typical solar spectrum and the sensitivity of a typical c-Si PV cell:

$$\tau_{cSi} = \frac{\int \tau_{Kor,G2}(\lambda) \cdot AM_{1.5}(\lambda) \cdot cSi(\lambda) \cdot d\lambda}{\int AM_{1.5}(\lambda) \cdot cSi(\lambda) \cdot d\lambda} \tag{A.5}$$

The solar spectrum with air mass 1.5 as defined in ISO 9845-1[1] “hemispherical solar spectral irradiance” is utilised. For the weighting of the c-Si sensitivity ($cSi(\lambda)$) the IQE (internal quantum efficiency) as published by Thomas et al. [2] for typical polycrystalline silicon cells is used, where the assumption that one photon only creates one electron pair is applied. The IQE is used because it is independent of the integration of the cell into the module or respective anti-reflex coatings used and represents the upper limit of an obtainable EQE (external quantum efficiency). Any absorption in the embedding material is neglected, even though the typical material such as EVA absorbs light in the uv-region. The spectral range affected by this simplification below 400nm only accounts for about 1.5 % of the relevant spectrum.

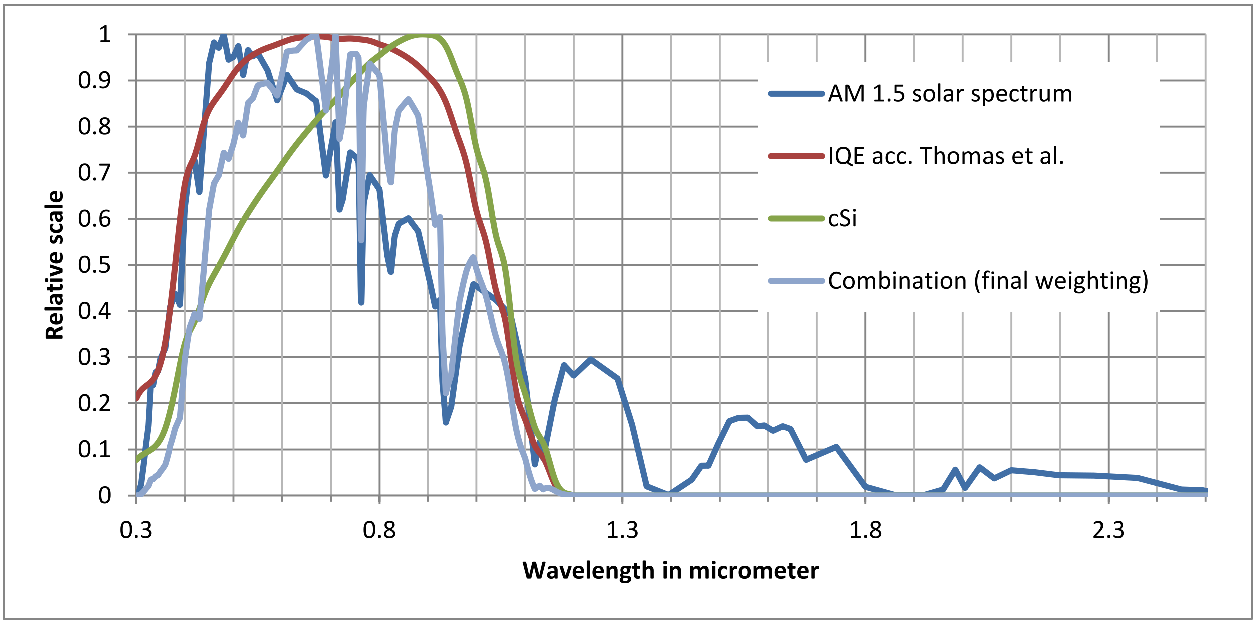

Figure 3: A plot of the weighted spectrums (normalised); the AM 1.5 standard solar spectrum, the utilised internal quantum efficiency (IQE) and the resulting c-Si efficiency. The *Combined Weighting* involves superimposing the c-Si and AM 1.5 weights via Eq. A.4.

Appendix B: Incident angle modifier factor $F_{IAM,PV}$

The incident angle modifying factor $F_{IAM,PV}$ quantifies the influence the angular dependence of transmission has on the annual solar yield of a typical PV module. It is defined as:

$$F_{IAM,PV} = min([F_V^T + F_H^L], [F_V^L + F_H^T]) \quad \text{(B.1)}$$

where:

$$F_{Geo}^{Axis} = \sum_n \left(IAM_n^{Axis}/IAM_{ref,n}\right) \cdot S_n^{Geo} \quad \text{(B.2)}$$

and

IAM_n^{Axis}	IAM-measurement at angular position n of an optically coupled glass and cell.
$IAM_{ref,n}$	Reference IAM-measurement of the cell with EVA embedding but without glass cover.
S_n^{Geo}	Coefficient for the angular position n
$n = 0, .., 5$	Index of angular position
$Axis \in (T, L)$	Axis of incident angular modification (Transversal, Longitudinal)
$Geo \in (V, H)$	Orientation of the glass (vertical, horizontal): horizontal axis lies parallel to the earth's surface. vertical axis and earth's surface define the inclination angle.

The coefficients S_n^{Geo} define the fraction of annual irradiation available at a given incident angle (n) for a south-orientated module in central Europe (Rapperswil, SG, CH) with a 30° inclination. Because the orientation of PV-modules is normally not specified (portrait or landscape) at installation, the poorer performing variant is used to assess the glass. The measured incident angles and their respective coefficients S_n^{Geo} are given in Table 2.

Table 2: The incident angle modifying factor S_n^{Geo} reflects the fraction of annual irradiation incident at a given angle for a south-orientated module in Rapperswil, SG with a 30° inclination to the horizon.

n	0	1	2	3	4	5
Angle [°]	0	30	40	50	60	70
S_n^{Ver}	0.068	0.121	0.078	0.055	0.036	0.027
S_n^{Hor}	0.070	0.194	0.108	0.097	0.087	0.059

The influence of a glass on the IAM response of PV modules is measured with a test-cell. This cell has an *active* dimension of 20x20mm. A laser diode providing homogenous collimated light and spread to approximately 60 mm diameter is used as a source. Its 650 nm wavelength lies in the middle of the weighting spectrum (see Appendix A). As could be shown in model calculations and measurements[3], this monochromatic measurement can be seen as a representation for the complete range of wavelengths.

Due to the heavy dependence of the IAM response on the polarisation of the light source, either a completely un-polarised light must be used or two measurements rotated 90° are averaged. For reference the IAM response of a reference cell (polycrystalline silicon from a leading company embedded in 0.5 mm EVA) is used. The glass is coupled to the EVA embedding material with a glycerine film. The weighting factors are determined from annual simulations. With the Software Polysun 5[4] the annual irradiation is calculated in dependence of the incident angle. Polysun 5 uses weather data from Meteonorm 6[5], in which an anisotropic diffuse irradiation model following Perez et al.[6] is used.

The sum of irradiation encountering the module at a given incident angle n over a year defines the coefficient for weighting S_n^{Geo}. In the case where an incident angle lies between two supporting points, the irradiation is linearly subdivided into the two respective *bins*. For example, irradiation incident at 10° increases the coefficient for 0° by two thirds and 30° by one third of the irradiation incident at that angle over a year. The measured difference in IAM sensitivity between the coupled glass cell and the reference cell (with EVA but without glass) for a given angle is weighted with the annual irradiation incident at that angle on the reference module.

The reference module is defined as south orientated with an inclination angle of 30° and located in Rapperswil (SG, CH). An investigation of differing orientations and locations (Madrid, Rapperswil Freiburg and Stockholm) showed that the distribution of irradiation between locations varied little and differing orientations led to similar coefficients. In the case of very steep inclination angles (e.g. facade integration) there is however a significant difference in irradiation distribution. For the certification of glass coverings this special case is not considered however, due to its rarity.

Appendix C: Photolysis factor $F_{UV,PV}$

The Photolysis factor defines the degradation of transmission due to UV-radiation triggered Solarisation. The factor quantifies the influence this degradation has on the annual yield of a PV module. It is defined as follows:

$$F_{UV,PV} = \frac{\tau_{cSi}^{UV}}{\tau_{cSi}^{ref}} \tag{C.1}$$

Here, τ_{cSi}^{UV} defines the backside-interface-corrected transmission factor (Appendix A) of the unexposed glass and τ_{CSi}^{UV}, the same factor after the glass has been irradiated with UV light. Any change in transmission factor occurs mostly due to a change in internal extinction or the anti-reflex coating on the front side. This can be approximated quite well with the change in direct-hemispheric transmission without backside-interface-correction (see also Eq. A.2):

$$\frac{\tau_{tot}^{UV}}{\tau_{tot}^{ref}} = \frac{(1-r_1^{UV})(1-r_2^{UV})t^{UV}}{(1-r_1^{ref})(1-r_2^{ref})t^{ref}} * \frac{(1+r_1^{UV}r_2^{UV}(t^{UV})^2+...)}{(1+r_1^{ref}r_2^{ref}(t^{ref})^2+...)} \tag{C.2}$$

The variables in Eq. C.2 are wavelength dependent. This is however not shown in notation for reasons of clarity. On the assumption that the reflection at the interface is around 4% (typical glass) or significantly lower (anti-reflex coatings), it can be shown that the first multiple reflection makes up for less than 0.16% of the transmitted light. Every further multiple reflection accounts for a factor 1000 less, and as such is neglected. Further, the reflection at the backside interface is considered unchanged by UV exposition, allowing Eq. C.2 to be simplified without accounting for $(1-r_2)$ and multiple reflection to:

$$\frac{\tau_{tot}^{UV}}{\tau_{tot}^{ref}} \approx \frac{(1-r_1^{UV})t^{UV}}{(1-r_1^{ref})t^{ref}} * \frac{(1)}{(1)} = \frac{\tau_{Kor,G2}^{UV}}{\tau_{Kor,G2}^{ref}} \tag{C.3}$$

In this way we can approximate the backside-interface-corrected transmission following UV exposition with the backside-interface-corrected transmission of the un-exposed glass:

$$\Rightarrow \tau_{Kor,G2}^{UV} \approx \tau_{Kor,G2}^{ref} * \frac{\tau_{tot}^{UV}}{\tau_{tot}^{ref}} \tag{C.4}$$

τ_{cSi}^{UV} can thus be determined with Eq. A.4. Through this simplification separate measurements of the direct hemispheric reflection with and without light trap are not necessary. The error associated with this simplification amounts to around 0.0002 with a 5% change in internal transmission across the whole light spectrum (which worst case would lead to a classification in the last class). A change in the front side interface is in the case of anti-reflex coatings possible. However, even in the case of a significant change in the anti-reflex coating of the order of Δr_1=0.02 (which amounts to a halving of the maximal improvement an anti-reflex coating can achieve), the associated error lies under 0.1%. The change in a tested glass through solarisation (relative to its original condition) can thus be quantified accurately enough without interface-correction.

The exposure should consist of at least 80 kWh/m^2 of UVA and 3 kWh/m^2 of UVB. This equates approximately to the amount of UV exposure expected in one year in central Europe.

Appendix D: Glass-certificate as a basis for quality control

The SPF solar glass certificate is used by many manufacturers from PV modules as a basis for quality control. To ensure that this remains the case, SPF recommends the observation of the following points:

The technical specifications should be explicitly note the certificate classification as listed in Section 3.3. It is also worth noting that both glass material and surface coating are covered by the certificate. In the contractual arrangements (e.g. Delivery specifications, quality control agreements, orders etc.) it is worth anchoring the certification number in the duties regarding distribution of certified glass. Module manufacturers are advised to test random glass samples at SPF in the framework of *incoming goods inspection*. It is also recommended to refer only to reference measurements made by SPF. In this way a high quality control is ensured.

These recommendations relate only to the optical properties of the glass. All further aspects (e.g. tolerances, hardness, etc.) are to be considered separately.

Appendix E: Further documents and information

Glass in building; tempered safety glass, concepts, dimensions, processing, specifications, German Standard DIN 1249, Part 12

Glass in building, Basic soda lime silicate glass products - Part 5: Patterned glass, European Standard EN 572-5, November 1994

www.spf.ch

References

[1] „ISO 9845-1:1992-10 Solar energy; reference solar spectral irradiance at the ground at different receiving conditions; part 1: direct normal and hemispherical solar irradiance for air mass 1,5", International Organization for Standardization, Genève, Switzerland, 1992.

[2] C.P. Thomas, A.B. Wedding, und S.O. Martin, „Theoretical enhancement of solar cell efficiency by the application of an ideal 'down-shifting' thin film", *Solar Energy Materials and Solar Cells* 98, No. 0 (2012): 455–464.

[3] F. Ruesch, L. Omlin, S. Brunold, „Solarglas-PV- Schlussbericht", Schweizerisches Bundesamt für Energie BFE, 2012.

[4] *Polysun 5.2*, Velasolaris, Winterthur, Switzerland, 2011, www.velasolaris.ch.

[5] *Meteonorm 6.1,* METEOTEST, Bern, Switzerland, 2009, www.meteonorm.com.

[6] R. Perez R. Steward, C. Arbogast, R. Seals, J. Scott, „An anisotropic hourly diffuse radiation model for sloping surfaces: Description, performance validation, site dependency evaluation", *Solar Energy* 36, Nr. 6 (1986): 481–497.