Quantification of abrasion-induced ARC transmission losses from reflection spectroscopy

Klemens Ilse[1,2], Charlotte Pfau[1], Paul-T. Miclea[1], Stephan Krause[1,2], Christian Hagendorf[1]

[1]Fraunhofer Center for Silicon-Photovoltaics CSP, D-06120 Halle (Saale), Germany

[2]Anhalt University of Applied Sciences, D-06366 Köthen (Anhalt), Germany

Abstract — **Front side anti-reflective coatings (ARC) provide a significant contribution to performance and energy yield in PV modules, solar thermal housings and green house applications. However, ARC degradation and abrasion may lead to long term losses in optical performance. In order to quantify these losses and bench mark various ARC in abrasion testing, a non-destructive optical assessment of the ARC performance in large samples is required.**

Here, we present a methodology for the quantitative measurement of front side ARC performance and its impact on optical transmittance from a simple reflection spectroscopy measurement using a commercial spectrometer and a broad band absorber for reflection suppression at the glass back side. Results on reflection spectroscopy are presented on standard ARC coated solar glasses with and without internal reflection suppression, which represent the application scenarios in PV modules and green houses, respectively. The optical transmittance of the front side ARC is calculated via a simplified approach based on the law of energy conservation. A validation is performed by comparing spectra determined with the adapted experimental characterization method with optical calculations. Finally, the simplified method for a quantitative optical front side ARC assessment of full size glass panes is applied in successive and gradual ARC abrasion experiments.

Index Terms — **glasses, antireflection coatings, optical spectroscopy, PV modules, optical modeling, broad band absorption, methodology.**

I. Introduction

Optical transmission, reflection and absorption of coplanar glass plates is strongly influenced by coatings and surface structures. Material properties and deposition processes have to be precisely controlled in order to meet the desired spectral properties.

Anti-reflective coatings (ARC) for solar modules, enclosures for concentrated solar power and greenhouses have to provide a maximum intensity transmission in specific regions of the solar spectrum. Typical reflection losses at the bare air/glass interface of a solar module are about 4%. As the industry is driving towards higher efficiencies, it has widely adopted ARC for solar module front cover glass. It is estimated that more than 70% of silicon PV modules nowadays ship with ARC front glasses [1].

Since glass panes usually exhibit at least two surfaces/interfaces (front and back side), the standard measurement setup for optical transmission and reflection [2-4] results in an integral value for the complete layer stack comprising front side, bulk material and back side. Thus, it is a complex and time consuming task to distinguish between the contribution of the different surfaces and coatings based on transmission and reflection of the complete system. A detailed analysis requires extended spectroscopic investigation and optical simulation. Furthermore, large and hardened glass panes from industrial productions do not allow the use of standard laboratory equipment due to lacking preparation techniques.

However, in many cases it is mandatory to evaluate optical transmission and reflection for front and back surfaces separately. Typical questions that address just one particular side of a glass are benchmarking of ARC from different deposition processes, evaluation of mechanical abrasion behavior or data acquisition for computational optics. While a small minority of suppliers still provide vacuum deposition based ARC, the vast majority of traditional coatings are based on single layer, porous silica, wet sol-gel technology [5], [6]. These coatings typically derive their mechanical strength through a high temperature sintering step that occurs when the PV cover glass is tempered. As the PV industry has grown PV module manufacturers and system owners and operators are increasingly focused on levelized cost of electricity. With growing experience in the long-term field performance of these coatings they are seeking ARC glass with increased durability and long-term performance, particularly for systems operating in medium to high soiling environments, where PV modules are subjected to airborne particle abrasion (e.g. blown sand or dust) and repeated cleaning [7], [8].

In this work, we are presenting a measurement approach that allows us to calculate the optical transmittance from a reflectance measurement using a standardized commercial spectrometer according to a standardizes measurement procedure e.g. IEC CD 62805-2/IEC:2015. This nondestructive technique is applicable to large samples in the range of several m². Firstly, we will describe the underlying physical assumptions and prerequisites of our advanced sample setup. We will present the required experimental instrumentation. Experimental results on optical transmittance and reflectance will be shown for glasses with and without ARC and evaluated according to the proposed method. The experimental results will be compared and verified by optical calculations. Finally, the method is used for the quantification of ARC performance losses of full size glass panes subjected to an adapted abrasion test procedure.

II. THEORY

A. A simplified Law of Energy Conservation (LoEC) approach to optical front side transmittance of solar AR coatings from spectral reflectance measurement

Light intensity in our sample systems for PV (air/ARC/glass/EVA) and greenhouse (air/ARC/glass/air) applications follows the law of conservation of energy. As a consequence the total transmittance τ, reflectance ρ and absorptance α of the system has to fulfil:

$$1 = \tau + \rho + \alpha . \qquad (1)$$

In our simplified model, any glass with or without ARC coating is considered as a system, which can be described by a few fundamental ingredients, being the intensity reflection factors R_{FS} and R_{BS} of the glass front and back side, respectively, and the absorption constant a_{glass}. The intensity reflection factors, simply give the ratio of reflected and incoming light beam intensity of the glass front or back side which is always treated as a single interface. The absorption constant a_{glass} is the decay constant of light intensity decreasing exponentially with the penetration depth into the bulk glass body [9]. The contributions of the interfaces and bulk material absorption along the optical path due to multiple reflections is shown in Fig. 1 a.

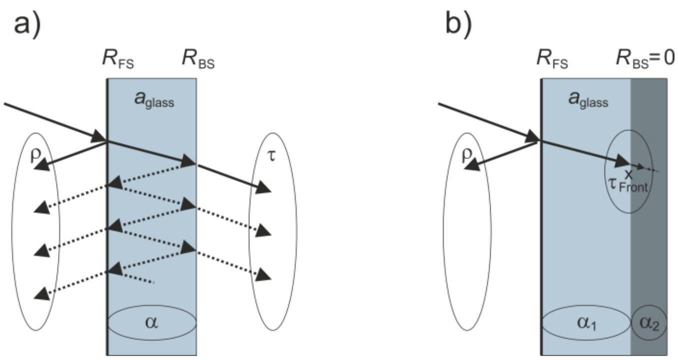


Fig. 1. Optical conditions of the incoming light intensity of glass in air (a) and a glass with index matching at the back side (b) corresponding to the sample systems for greenhouse and PV applications, respectively.

The measured global hemispheric reflectance ρ and transmittance τ of glass in air with thickness d can be calculated by summing up all contributions as indicated in Fig. 1a [10]:

$$\rho = R_{FS} + (1 - R_{FS})^2 \cdot R_{BS} \cdot (\mathrm{e}^{-a_{glass} \cdot d})^2 \sum_{n=0}^{\infty} R_{FS}^n \cdot R_{BS}^n (\mathrm{e}^{-a_{glass} \cdot d})^{2n} \qquad (2)$$

$$\tau = (1 - R_{FS}) \cdot (1 - R_{BS}) \cdot \mathrm{e}^{-a_{glass} \cdot d} \sum_{n=0}^{\infty} R_{FS}^n \cdot R_{BS}^n (\mathrm{e}^{-a_{glass} \cdot d})^{2n} \qquad (3)$$

The equations are valid if the reflections at the interfaces are perfectly specular or Lambertian, for all specifically scattered reflections they are an approximation.

For the direct determination of R_{FS} and R_{BS} at the glass front and back side with experimental methods, our approach is to suppress the back side reflection by a broad band absorbing material in the UV-VIS-NIR range. As shown in Fig. 1b, it absorbs simultaneously the front side transmittance τ_{Front} (%), that has passed front side ARC and the glass substrate. The front side transmittance τ_{Front} is independent of the optical design of the glass back side, e.g. glass/air or glass/EVA. Thus, it allows a comparative assessment of the front side ARC performance of glass in different applications like photovoltaic modules or green houses, respectively. The front side transmittance τ_{Front} cannot be measured directly. However, if R_{BS} can be completely suppressed and becomes negligible the measured reflectance ρ of the whole stack will be determined by the ARC front interfaces resulting in a strong simplification of eq. 2, being

$$\rho = R_{FS} \qquad \text{(for } R_{BS} = 0\text{)}. \qquad (4)$$

Here, the front side transmittance τ_{Front} defines a figure of merit describing only the contribution of the front side to the optical performance of the glass independent of the present back side properties. Setting $R_{BS} = 0$ in eq. 3, correspondingly, we can write the front side transmittance τ_{Front} as:

$$\tau_{Front} = (1 - R_{FS}) \cdot \mathrm{e}^{-a \cdot d}. \quad \text{(for } R_{BS} = 0\text{)} \ (5)$$

Since R_{FS} is directly measurable with the backside absorber and a_{glass} is known from the bare glass, this law of energy conservation (LoEC) based method allows a simple quantitative comparison of the ARC front side performance in photovoltaic modules (glass/EVA back side) or green houses (glass/air back side). In the following, the accuracy of the LoEC method will be evaluated based on experimental results and optical calculations of ARC/glass sample systems.

III. METHODS

A. Sample description

For the initial spectroscopic investigations in this study, lab size 20 cm x 20 cm x 3.2 mm float glass without and with ARC was used. The abrasion experiments were performed with coated samples from industrial production having large sample formats of 1 m x 2 m x 3.2 mm that cannot be cut because of toughening/tempering. These industrial glasses are highly anti-reflective, state-of-the-art solar grade low iron glasses. The ARC is a sputtered gradient nano-porous SiO_2 ARC layer of approximately 100 nm thickness and an average refractive index of $n_{ARC} \approx 1{,}4$. Front and back surface are coplanar.

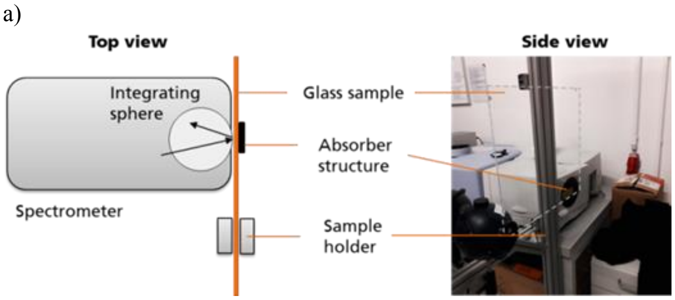
B. Reflection spectroscopy and optical calculations

The spectral transmittance and reflectance measurements were performed using a Perkin Elmer Lambda 1050 UV-VIS-

NIR spectrophotometer with implemented 150 mm integrating sphere providing a measurement uncertainty by a standard deviation of less than 0.1% in the VIS and NIR and 0.2% in the UV. It enables the quantification of spectral reflectance and transmittance as well as scattering properties, schematically illustrated in Fig. 2 a (top view). The measurement of the hemispherical reflectance has been performed according to IEC CD 62805-2/IEC:2015 (wavelength 300 to 1700 nm), whereby all measurements were carried out with incident light from the coated side. The measurement of the reflectance of samples with extended dimensions was performed as shown in Fig. 2 a (side view). The glass pane was placed on a frame adjustable in x and y direction directly at the output of the reflectance measurement device.

For optical index matching [11] and reflection back side reflection suppression as described in section II.A, a broad band absorber foil was laminated with ethylene vinyl acetate foil to the back side of the samples (Fig. 2b). The used ultra-black foil from *ACM coatings* provides a specular reflectance of only 0.1% at a band width from 100 – 10000 nm, the corresponding hemispherical reflectance is 1% [12]. The performance of this sample setup in suppressing back side reflections was investigated by the comparison of the optical data obtained with and without absorber structure.

a)



b)

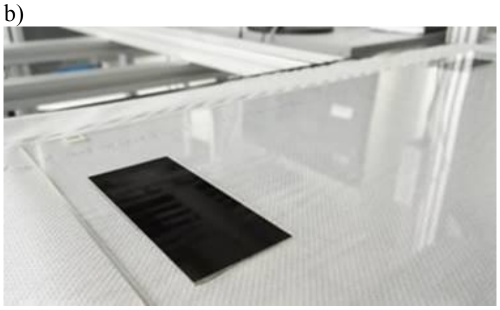


Fig. 2. a) Reflectance/transmittance measurement setup for large samples schematically in top view (left) and as experimental setup in side view (right). b) Detail view of a glass pane with the broad band absorber applied to the back side.

From the standard reflectance and transmittance measurements without absorber, the front side intensity reflection factors were calculated for the bare glass and ARC glass by solving the implicit eq. (2) and (3). Those were compared to intensity reflection factors which are directly obtained from the reflectance measurements of the samples with the absorber structure on the back side. Additionally, the intensity reflection factors obtained with the absorber method were used to calculate the spectral transmittance for further validation.

C. Abrasion testing

For abrasion testing, large scale glass samples were subjected to a brush test developed at Fraunhofer CSP in accordance with testing procedures provided in ISO 11998, ASTM D2486 and DIN EN 1096-2, which needed to be adapted to meet the requirements for simulation of harsh dry cleaning. For this, 1 g of Arizona Test Dust A2 fine (defined in ISO 12103) was homogenously distributed on the glass surface, covering the full area to be brushed. The brush (Nylon, 454 g, 5/4 pattern, see ASTM D2486) was then placed on top of the dust and moved perpendicular to the surface with an average speed of 24 cm/s and an effective scrubbing length of 70 mm. The bristles of the brush are comparably stiff and do not bend during testing, which – together with the high contact pressure according to the weight of brush and the test dust – causes high mechanical loads to the surface. For testing, a set of 100, 300, and 500 brush cycles was applied to the coating, whereby 0.5 g of test dust were re-deposited every 100 cycles. It can be assumed that this test procedure reflects a worst-case scenario for dry manual cleaning.

III. Results & Discussion

A. Reflection spectroscopy of solar ARC layers on glass and calculation of the optical front side transmittance based on the LoEC approach

Optical reflection spectroscopy was performed at the lab size standard solar glass with and without ARC. In Fig. 3 a, the spectral reflectance is shown for the samples without application of the absorber on the back side. The spectra show the expected typical reflectance behavior. The ARC glass presents a decrease of reflectance at around 500 nm to slightly below 6%, while the bare glass has an almost constant 8% reflectance over the complete UV/VIS/NIR spectral range. After application of the absorber to the back side of both samples (Fig. 3 b), the spectra exhibit a reduced reflectance of about 4%. This corresponds to the typical reflection loss of a glass/air interface present at the back side without absorber. The overall 4% drop in spectral reflectance for ARC/glass as well as bare glass samples, indicates that the back side reflection on glass/absorber interface is efficiently suppressed and negligible. Furthermore, the difference in both measurements with and without absorber structure, are indicative for the optical transmission of the glass in PV modules and green house scenarios.

With the LoEC approach it is possible to calculate the front side transmittance τ_{Front} from the measured reflectance of the sample with the absorber on the back side ($\rho = R_{\mathrm{FS}}$) based

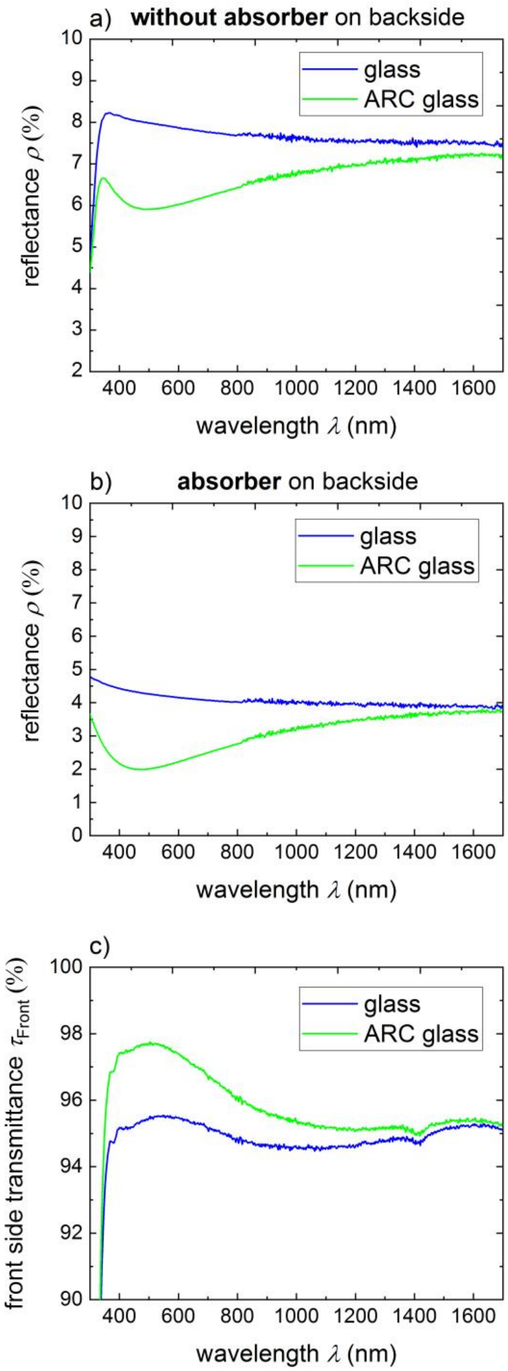


Fig. 3. Spectral reflectance of the samples without (a) and with (b) backside absorber that is suppressing the backside reflection. The hemispherical spectral transmittance of the glass front side τ_{Front} (c) is calculated from the reflectance without backside reflection and the bulk absorption determined on uncoated glass samples.

on the bulk absorption of the glass. τ_{Front} of the glass with and without ARC is shown in Fig. 3c as calculated by eq. 5.

For the bare glass, the front side transmittance is about 95% with about 4% being reflected at the front side and about 1% absorption loss when passing the glass ($e^{-a \cdot d}$ is between 99.7% - 98.5%). With the ARC on the glass, the front side transmittance increases to a maximum value of above 97,8% at 500 nm. The spectrum corresponds well to the reduced reflectance by the ARC (compare Fig. 3b and 3c). Since the absorption loss in the bulk glass is comparatively small, the transmittance τ_{Front} for both glass samples is dominated by the reflection of the glass front side. This demonstrates the importance of the ARC performance and durability.

B. Optical calculations and comparative evaluation of the method

The back side reflection suppression and calculation of transmission properties is further evaluated by comparing spectra determined with the back side absorber and with conventional glass characterization methods. In case of complete back side reflection suppression, the spectral reflectance measured on glass samples with the back side absorber is equivalent to the front side intensity reflection factor R_{FS} (compare section II.A). With conventional methods, the front side intensity reflection factor R_{FS} is determined by measuring the reflectance ρ as well transmittance τ of a glass in air and by subsequently calculating R_{FS} from the equations (2) and (3). The equations are solvable if the front side and back side intensity reflection factors R_{FS} and R_{BS}, respectively, are identical or if one of them is known. For uncoated glass R_{FS} and R_{BS} are identical ($R_{\mathrm{FS}} = R_{\mathrm{BS}} = R_{\mathrm{glass}}$) and R_{glass} can be calculated in a first step. Subsequently, for the same glass with an ARC on the front side R_{BS} is known ($R_{\mathrm{BS}} = R_{\mathrm{glass}}$) and thus R_{FS} of the ARC glass ($R_{\mathrm{FS}} = R_{\mathrm{ARC\ glass}}$) can be calculated. The reflection factors R_{glass} and $R_{\mathrm{ARC\ glass}}$ determined in this way are shown in Fig. 4a. They are compared to those measured directly with the back side absorber. For both samples, the spectra obtained with the different methods coincide very well. The maximum deviation is about 0.3%. This corresponds approximately to the measurements uncertainty of the device being 0.2%. Further deviations can be attributed to residual reflections from the absorber foil at the back side of the glass. They can be assumed to be similarly small since the specular reflectance is in the range of 0.1% and a substantial part of the light which is scattered into larger angles does not leave the glass due to internal total reflection. The well coinciding spectra further confirm that intensity reflection factors can be precisely determined with the presented back side absorber method.

Fig. 4b shows the transmittance spectra that are calculated from the reflectance measurements with back side absorber by inserting the corresponding R_{FS} and R_{BS} in eq. (3). The calculated data are compared to experimentally obtained spectral transmittance showing an average deviation of well below 0.5%. Thus, the method is well suited for the quantitative and non-destructive assessment of the ARC performance for optical transmission of large glass samples from reflection spectroscopy.

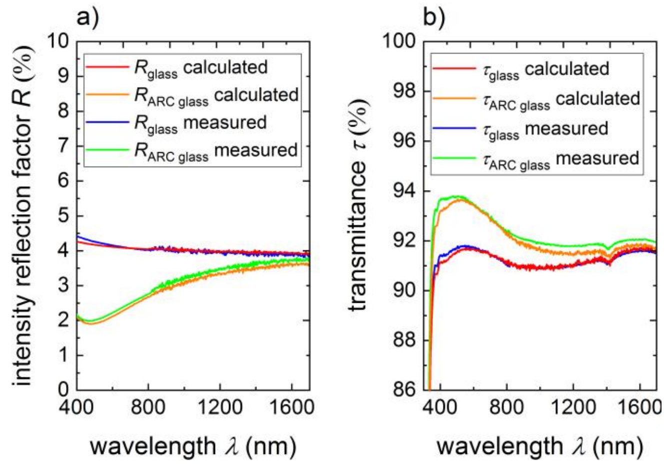


Fig. 4. Comparison of results obtained with the absorber structure and with conventional glass characterization methods. a) Intensity reflection factors of the bare glass and ARC glass front side determined from the transmittance and reflectance spectra by solving the implicit equations (2) and (3) in comparison to those determined directly from the reflectance measurement with back side absorber. b) Hemispherical spectral transmittance calculated from reflectance measurement in comparison to experimental transmittance spectra.

C. Reflection spectroscopy data obtained for sample series after gradual abrasion experiments: Reflectance and ARC thickness

Finally, the LoEC approach was applied to evaluate the transmission of various large area glass sheets after abrasion experiments at the ARC front side based on reflectance measurements. The coated glass samples were tested with a dry cleaning brush test setup at 100, 300 and 500 brush cycles according to the specification provided in section II.C. Accordingly, reflection spectroscopy was applied to obtain data for a series of samples after these gradual ARC abrasion experiments. As described in previous parts, the back side reflection contribution can lead to a systematic error in evaluation the front side reflection (ARC performance). A more precise quantification of the impact of the front side ARC abrasion due to cleaning processes can be provided by the optical characterization with an absorber structure at the back of the glass sample, which therefore was applied to all stressed ARC samples.

Fig. 5 a) shows the results of reflectance measurements of an uncoated (no ARC), a coated but unstressed (ARC 0 cycles) and stressed ARC samples after 100, 300 and 500 brush cleaning cycles. According to the considerations in section II, these displayed results correspond to the reflectance at the front side, since the contribution of the rear side can be neglected due to the application of the absorber structure.

By comparing the unstressed samples with and without ARC, the AR benefit introduced by the coating can be clearly seen. Furthermore, a clear gradual reduction of the AR benefit

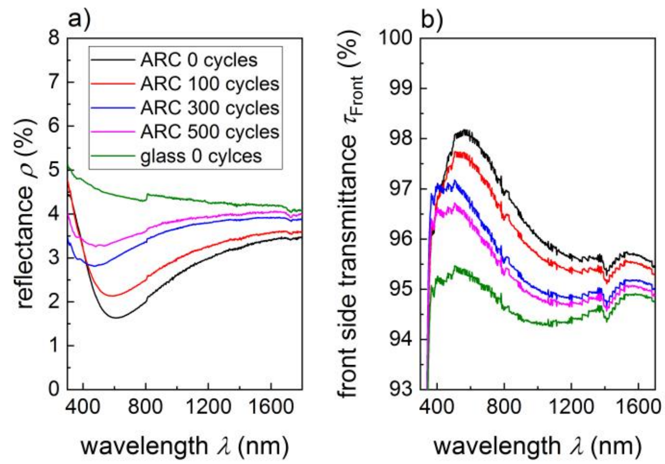


Fig. 5. a) Spectral reflectance with back side absorber structure indicating the front surface intensity reflection factor R_{FS}. b) Spectral transmittance of the front side calculated from the reflectance measurements via LoEC approach (eq. 5).

with increasing brush cycles can be detected, with the ARC still showing anti-reflective properties after 500 cycles of harsh cleaning testing. Further, a small blue shift in the minimum value of the curves is observed, which can be attributed to a thinning of the coatings during abrasion.

From the measured reflectance data, the transmittance at the front side was calculated according via eq. 5 using the simplified LoEC approach (Fig. 5b). For this, the absorption coefficient a_{glass} was determined from transmittance and reflectance measurements of an uncoated glass sample.

From the presented results in Fig. 5b), the benefit of the ARC for increased light transmittance and its gradual reduction with an increasing number of cleaning cycles becomes obvious. For example, the maximum of transmittance decreased from a value of about 98.1% (0 cycles) to 97.6% (100 cycles), 97.0% (300 cycles) to 96.6% (500 cycles), which is still above the glass reference with a maximum of 95,3%. In addition, the integral increase of transmitted light at the front surface for the undamaged ARC (0 cycles) compared to uncoated glass was calculated to be about +2.1 % for the wavelength range between 300 and 1200 nm, being reduced to about 1.2% after 500 cycles of abrasion.

The uncertainty of the measurement device and the applied appraoch can be estimated to be below 0.3%, but it estimated that an additional uncertainty of 0.5% is introduced through the large sample configuration, coating and abrasion inhomogeneity, positioning errors as well as relative humidity during measurement.

IV. Conclusion

The front side interface intensity reflection factors of uncoated and AR coated large glass panes were directly and non-destructively determined from measurements of the global hemispheric reflectance by suppressing the internal back side reflection with a broad band absorber structure. The spectral transmittance was calculated by a simplified LoCE approach based on the intensity reflection factors and the absorption constant and compared to experimental data. The novel approach was successfully validated resulting in a deviation of <0.5% between experimental and calculated spectra. A significant reduction of the front side transmittance after brush dry cleaning/abrasion tests showed that ARC are very sensitive to typical harsh dry cleaning conditions. Since ARC layers on the solar panel are most heavily subjugated to the stresses of the external environment, coatings with high durability are crucial for PV systems deployed in the field with lifetimes of multiple decades.

V. Acknowledments

This research was funded by the federal state of Sachsen-Anhalt in the EFRE project “MetroLarge” (IB Sachsen-Anhalt, 1804/00012) and the Federal Ministry of Economic Affairs and Energy of Germany in the project “ROSE” (BMWi, 03TNH022A).

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