FROM THE IMPACT OF HARSH CLIMATES AND ENVIRONMENTAL CONDITIONS ON PV-MODULES - DEVELOPMENT OF A SOILING AND ABRASION TEST

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ABSTRACT: Predicted energy yields are only achieved, if the impact of a location with its specific abrasion and soiling properties on PV-modules is known, especially in harsh climates like deserts with sand storms, fine dust and arid conditions. Functional materials like structured glass, anti-reflective coatings (ARC) and anti-soiling-coatings (ASC) are supposed to guarantee higher yields. But keep these products there promises and how stable are they? Maintenance and material choice can be adapted to the location, but therefore it is necessary to determine properties and functionality of the module surfaces. Such tests enable to benchmark materials, allow to determine the effects on the modules output and to investigate their long-time resistance. The results show that soiling depends on surface morphology and tilt angle. Prismatic and pyramid structured glasses soil easier especially under flat angles in flat-roof integrated systems or equatorial regions. To investigate self-cleaning properties of surfaces a test method is presented. The results show that ASC can help improving the self-cleaning properties and therefore improve the yield of a PV system. An abrasion test is presented and enable to investigate the abrasion on coatings due to soil or cleaning devices. Moreover, the impact of certain cleaning devices on the module quality is investigated in special procedures.

Keywords: Soiling, Abrasion, Non-Standardized Testing

1 Introduction

In the past three years the global PV market changed dramatically. More and more PV installations are build up in regions closer to the equator line, where it is possible to harvest more of sun's energy. But beside the fact of higher irradiation (kWh/m²) those regions can tend to show more sedimentation. Effects due to sand and dust deposition in arid regions as well as from air pollution became more and more important because soiling in such regions is a considerable problem and need technical solutions.

Despite the fact that research in this field lasts already seven decades there is still a lack of knowledge and there are still challenges to be solved. Sarver et al. gives an excellent and "Comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches" [1]. Mani and Pillai contributed a useful categorization of climatic zones and recommend cleaning schedules [mani2010].

Each location has its specific abrasion and soiling properties on PV-modules, especially in severe climates like deserts with sand storms, fine dust and arid conditions. Other locations have its special environmental impact due to agriculture or industrial pollution. Abrasion and soiling are part of the influencing factors for yield losses and reduced module life-times and therefore underline the necessity of monitoring module plants. In consequence maintenance and material choice can be adapted to the location. For this reason, it is necessary to determine properties and functionality of the module surfaces. So far, there exists no PV standard for specifying soiling and cleaning behavior (self-cleaning) of glasses or anti-soiling-coatings (ASC) of modules. Moreover, to qualify anti-reflective coatings or structured glasses the PV industry need specific tests to benchmark these materials, e.g. to determine the impact on the modules output and to investigate their long-time resistance. The sand and dust test enables to do this but is from our experience very intensive. [2] Alternatively, one can use tests from the glass industry. PI-Berlin adapted standards from the series "Glass in building - Coated glass". Part 2 deals with the "Requirements and test methods for class A, B and S coatings" and describe the abrasion test for ARC's and ASC's. [3] Part 5 describes the test method and classification for the self-cleaning performances of coated glass surfaces" [4].

This contribution is structured as follows: first the development of a soiling and abrasion test set up is presented as well as some experiments. These are long time outdoor exposure of different structured glasses and modules, the determination of self-cleaning properties of different coated glasses, the investigation of different abrasion set-ups and the investigation on the long term resistance of different ARC's.

2 TEST SET-UP DEVELOPMENT AND EXPERIMENTS

2.1 Soiling Test

The soiling test is build up in accordance to the draft standard "Glass in building - Coated glass - Part 5: Test method and classification for the self-cleaning performances of coated glass surfaces" prEN 1096-5:2011 [4]. The procedure is adapted according to the first results obtained in the validation process. With the set-up shown in figure 1 it is possible to soil modules with an angular dependence. The modules can be mounted in there future installation manner or any other angle for experimental purposes. A special dirt liquid is used to pollute the surface and is sprayed with the pressure-dirt-unit (shown in the right picture of figure 1).

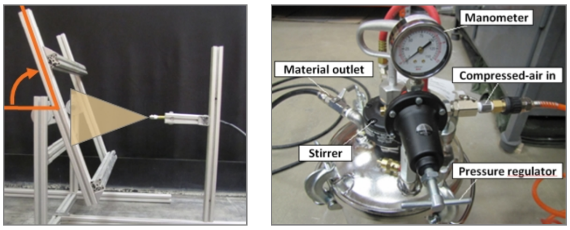

Figure 1: Soiling test bench with polluting rack and nozzle (left) and pressure-dirt-unit (right)

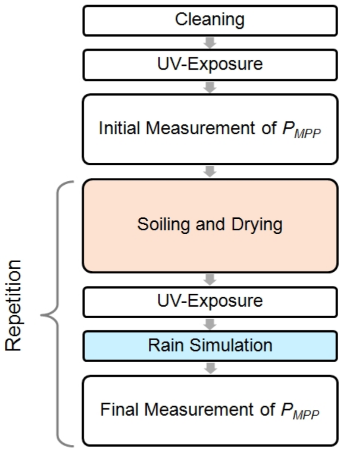

Figure 2: Test procedure to soil modules following the draft prEN 1096-5

The mixture is stirred together with soluble components and non soluble components acc. draft prEN 1096-5. Our suggested test procedure includes several UV-treatments, polluting, drying and artificial rain steps. Figure 2 shows the procedure in detail, which corresponds in most parts with the draft procedure. A first cleaning of the modules is followed by an UV-exposure acc. IEC 61215 (10.10) to activate the materials for 12 hours, which matches to 3 kWh/m². Afterwards an initial characterization of the modules is performed with visual inspection (10.1), power measurement under standard test conditions (10.2) for 1000 W/m² and weak light conditions under 200 W/m². Additionally, measurements under inclined irradiation were performed acc. to our house internal standard [6] to determine the power characteristic of a module in dependence to the angle of incident of light. Then the dirt mixture is sprayed with a flow rate of around 0.6 l/min over the modules. In total a volume of 30 ml of liquid, which correspond to a time spray of 3 seconds, is sprayed. The soiling is finished with a drying and an additional UV-exposure. To simulate the self-cleaning properties the module is sprayed with deionised water in the same angle of incidence like in the soiling section. A volume of app. 120 ml is sprayed with a flow rate of 0.48 l/min corresponding to 15 s of spray and dried at the end. Finally the module is characterized again in the initially performed tests. Haze measurements were not performed.

The soiling test was performed on glasses and on PV-modules. The glasses differ in its surface. The standard float glass had a flat surface, the next one a slightly structured surface and finally the third glass with a pyramid structure. The soiling influence of the surfaces were determined in using the soiled glasses as filter in front of a one-cell mini module and measuring its IV-curves using a Class AAA flasher Pasan SSIIIb with a measurement uncertainty of 2.1 % and a reproducibility of 0.3% for maximum power.

2.2 Outdoor Tests

On PI-Berlin's outdoor test site standard multi-crystalline modules were installed with different glass surfaces to determine the soiling behavior of the modules for this specific location and test site. The modules were installed from May 2011 to April 2012 for a period of 261 days. One module had a pyramid structure and the other one a flat glass. For determination of the soiling factor the modules were uninstalled and measured in the laboratory. The IV-curves have been determined using PI-Berlin's flasher system described above.

In another experiment we performed yield measurements. The yield measurements were performed from 3rd to 15th of September 2013 on modules with two different coatings. A Titanium dioxide (ASC 1) and Zinc and Silver dioxide (ASC 2) was tested. For this purpose three modules for each type, one without coating (ASC 0) and the other two with the coatings ASC 1 and ASC 2, are measured at the flash light sun simulator and logged outdoor for 13 days. Three different module types are tested for a total of nine modules.

2.3 Abrasion Test

For abrasion simulation, there is the same problem that no PV-standard exists. A standard "Glass in building - Coated glass - Requirements and test methods for class A, B and S coatings" EN 1096-2:2012 was used to build up the test equipment and procedures. [3] The abrasion was determined using different abrasion materials in a rotating movement. Figure 3 illustrates the test equipment for the abrasion test.

Figure 3: Abrasion tester, which was adapted to perform rotating movements instead of linear movements by using a gear wheel (right)

The abrasion testing apparatus was equipped with three different abradants varying in its hardness compared to an abrasion felt. The abrasion felt, which is provided in the standard, was used beside 3 types of wearaser abradants with its specific properties: CS17 elastic hard, CS10 elastic soft and CS10F elastic extreme soft. A stroke length of 100 mm, differing from the standard, which recommend 150 mm, and a velocity of 60 strokes per minute were applied in 50, 100, 250 and 1000 cycles. At the end of each stroke cycle a rotating movement of 30° is performed. A force of 4 N is applied to the sample via the abradants axis.

2.4 Transmission and reflective Measurements

The transmission and reflective measurements were used to evaluate the abrasion on the glass samples. The spectral terrestrial irradiation is reduced due to atmospheric absorption depending on the wavelength. That natural behavior has to be considered using a corrective calculation resulting in the transmission factor τ_e and reflection factor ρ_e. The factors can be calculated using the standard ISO 9050 [7]. The formula considers the AM 1.5g spectra S_λ in the wave length range of 300 to 2500 nm.

$$\tau_e = \frac{\sum_{2500\,nm}^{300\,nm} S_\lambda \cdot \tau(\lambda) \cdot \Delta\lambda}{\sum_{2500\,nm}^{300\,nm} S_\lambda \cdot \Delta\lambda} \qquad (1)$$

$$\rho_e = \frac{\sum_{2500\,nm}^{300\,nm} S_\lambda \cdot \rho(\lambda) \cdot \Delta\lambda}{\sum_{2500\,nm}^{300\,nm} S_\lambda \cdot \Delta\lambda} \qquad (2)$$

The abrasion effect is expressed by the quotient resulting from the final transmission after abrasion and reference, as well as for the reflection.

The used measurement device works in the range of 400 to 1000 nm. Therefore formula 1 and 2 were accommodated accordingly. The characterization of the samples was performed with a spectrometer system from tec5. A 50 W halogen lamp is used as light source. The measurement beam is transferred via optical fibre to the measurement head RTPSphere. This sample holder is capable for measuring each sample size (at the edge) and a maximum thickness of 6mm. A 50 mm integrating sphere enables to measure the scattered light e.g. on a structured glass (according producers manual). We could reach values for the measurement reproducibility of <0.1% for transmission and <0.8% for reflection measurement in the wavelength range from 400 to 1000 nm.

2.5 Sample description for abrasion tests and test methods

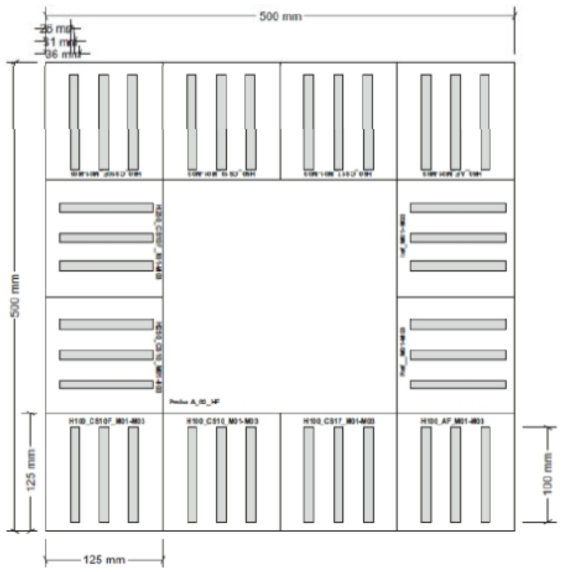

Figure 4: Glass sample preparation for abrasion tests. The grey lines are the abrasion markings

Glass samples of two different manufacturers with on market available SiO_2 coatings were used for the abrasion test. Glass A had an ARC manufactured with a sputter process and B with a roller coated ARC. Both float glasses are 500x500 mm² and differ in its thickness of 2.8 +/- 0.2 mm (A) and 3.0 +/- 0.2 mm. All glasses were subdivided in 12 measurement areas each for 3 abrasion areas and marked according the following stress tests (see figure 4). The glass samples were stressed with the abrasion test according to the description in subsection 2.3. Each stress was performed on three locations and the results were averaged.

2.6 Measurements under inclined irradiation

Anti reflective coatings promise higher transmission (T) and lower reflection (R) especially under inclined irradiation. The R- and T-measurements are performed wavelength resolved under a steady angle of incidence. To determine inclined irradiation behavior of coated glasses a flasher system with AM 1.5g spectrum and an apparatus to set the angle of incidence in the plane of incidence is used (Goniometer, see figure 5).

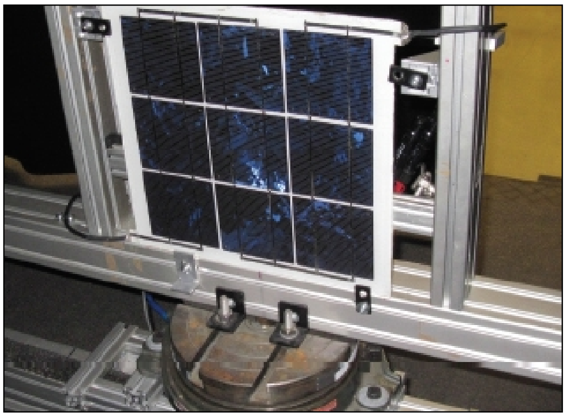

Figure 5: Goniometer used for the inclined irradiation measurements at the flasher system. In the plane of incidence the sample is symmetrically deflected around the rotation axis [6]

The measurement parameter are the short circuit current of a PV cell/module due to the linear dependence between irradiation and I_{sc}. If the behavior of a glass is to be determined the glass is used as filter in front of a reference cell. If the behavior of an abraded part of a glass is to be determined the area apart the abraded part is shadowed. If the behavior of a 60 cell module is to be determined only the middle string of the module is measured. A cosines correction was performed. We could calculate a measurement uncertainty of 2.75 % on the I_{sc} including random and systematic error in the measurement for angles up to 70°. For angles up to 80° the total uncertainty rises to 3% respectively 4.1 % at 85°.

3 RESULTS AND DISCUSSION

3.1 Long term outdoor exposure

The module power is reduced under a layer of soiling. How fast a module soil depends among others on the specific location and the surface properties. In Figure 6 the soiling behaviour is presented for two modules distinguishing in its glass surface. The standard module (grey) has a flat float glass and the other module (orange) a pyramid structure. The modules were installed at PI-Berlin's outdoor test facility (for details see 2.2). The indoor performed power measurements after 261 days reveal a power loss of -1.3 % for the standard module with flat glass and -4.8 % for the module with pyramid structure. For both modules a measurement uncertainty of 0.3 % is assumed. Comparing those results with the measurements after cleaning one can see that both modules soil, but the module with pyramid structure 3.7 times more. Both modules were installed in the same manner (identical tilt angle and module height on the rack) but show significant differences in the power reduction. Results from other groups seem to be rare but again Sarver gives an overview on the factors, which influence the initial adhesion of a dust deposition process. He states that "the initial adhesion depends on the surface itself, its composition, chemistry, morphology (smoothness, roughness), conductivity, charge, orientation, optical properties, hardness/softness, temperature, mechanical motion, and even down to micro- or nano-characteristics." [1]

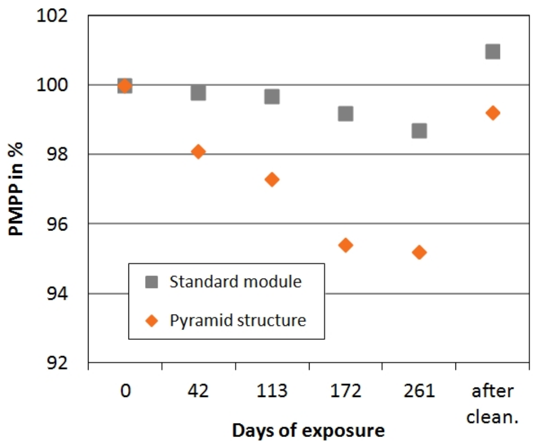

Figure 6: 261 days long time outdoor exposure of a module with pyramid glass structure vs. a standard module with flat structure. Power measurements were performed indoor in a flasher system. Finally, the modules were cleaned and measured again

3.2 Self cleaning properties of glasses

As well as the glass structure, the tilt angle among others is influencing the soiling behaviour. [8] Elminir et al. has shown, that the reduced transmittance depends strongly on the dust deposition density in conjunction with the tilt angle. Furthermore, the power reduction depends on the glass surface. Table I summarizes the results for both dependencies: tilt angle and surface structure. In section 2.1 the details for the soiling and self-cleaning procedure were described. In first dependency one can see, that a flat angle of 10° soil more than a tilt angle of 30°. In this specific case the resulting power drop is in average doubled. Additionally, the glass structure influences the results. A slightly structured glass behave in the same way like a (flat) float glass. The glass with prismatic structure show a significant reduction of power of -1.54 % (30°) and -3.70 % (10°).

Table I: Determined self-cleaning properties of different glass structures and tilt angles. The glasses were treated in two cycles of soiling and rain simulation

	Tilt angle of glass	
Power drop in % of	30°	10°
Float glass (flat)	-1.0	-1.9
Slightly structured glass	-1.3	-1.9
Prismatic glass	-1.5	-3.7

From these results one can conclude, that more attention is needed regarding cleaning issues, if modules are installed under flat tilt angles and especially, if they use structured glasses. This can concern potentially all modules installed flatly on roof tops.

3.3 Self-cleaning properties of modules

One method for reducing the soiling effects or cleaning efforts is to coat module glasses with self-cleaning layers [anti-soiling-coating (ASC)]. In this case a titanium dioxide (ASC 1) and zinc and silver dioxide (ASC 2) is tested and compared in yield measurements (see part 2.2), determination of self-cleaning properties (see part 2.1) and measurements under inclined irradiation (see part 2.5). Sarver et al. gives an overview of the historical and recent activities in the field of surface modifications and coatings as preventive mitigation technique and summarizes that the development of a coating that simply will not permit the dust to settle on the module surface is the Holy Grail for the prevention community. This is because it is a necessary and cost-effective way of action in multi MW-plants[1].

The specific energy yields of ASC 1 and ASC 2 vs. a reference module were determined in a one week outdoor installation. Table II shows the results. ASC 2 performs better than ASC 1 and gained 2.8 % more kWh/kWp compared to the reference. Compared to that result ASC 1 gained only 1.75 %.

Table II: Specific energy yields of ASC 1 and ASC 2 vs. reference determined in a one week outdoor installation

	Reference	ASC 1	ASC 2
kWh/kWp	31.46	32.01	32.34
Deviation to reference	-	1.75	2.80

In the next step, these three modules were examined to determine the self-cleaning properties. Figure 7 illustrates the evolution of the module power P_{MPP} after soiling and rain simulation. The first two cycles of soiling under an angle of 30° showed no significant power reduction. Therefore the soiling was repeated under an angle of 0°. A tilt angle of 0° means an installation for the module in equatorial orientation, which prevents the dirt solution from dropping away. Now, all modules soil significantly around 8 % to 10 %. After a defined rain simulation in an angle of 45° one can see differences in the self-cleaning properties of the modules. Both ASC's show a self-cleaning effect but differ in the amount of improvement. ASC 1 improves 1.8 % and ASC 2 improves 6.5 %.

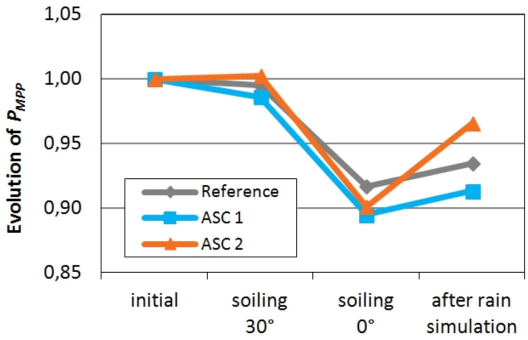

Figure 7: Comparison of two different coatings on standard mc-modules vs. reference. The self-cleaning property (P_{MPP}) is determined using a 30° and 0° soiling angle and a rain simulation

A further technique to evaluate the soiling and self-cleaning properties is to measure under inclined irradiation. Figure 8 presents the results of ASC 1 and ASC 2. The normalized I_{sc} is plotted over the module angle inclined from 0° (STC) to 85°. The results are plotted for the initial measurement (grey), after soiling (red) and finally after rain simulation (blue). Comparing the results from ASC 1 to ASC 2 one can see, that ASC 1 shows slightly flatter curves. This can explain the difference in determined yield difference like shown in table II. The main difference occurs for the measurement result after the rain simulation (blue compared to red one). ASC 1 gives only a very slight improvement after the cleaning whereas ASC 2 shows an improvement to I_{sc}-values, which are comparable to the initial state before soiling.

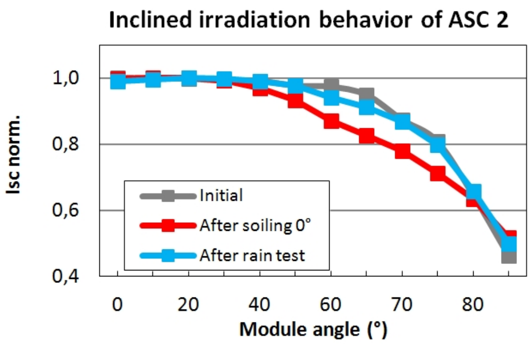

Figure 8: Inclined irradiation measurements of ASC 1 and ASC 2. The normalized I_{sc} is plotted over the module angle inclined from 0° (STC) to 85°. The results are plotted for the initial measurement (grey), after soiling (red) and finally after rain simulation (blue) to show the self-cleaning effect of the ASC. The measurement is cosines corrected

The results show that the anti-soiling-coatings tested can help improving the self-cleaning properties and therefore improve the yield of a PV system. A very important point is the investigation on such ASC's concerning their long term reliability in terms of abrasion. Despite natural wear and tear - modules are exposed to abrasion due to restorative mitigation techniques like from automated cleaning devices. This issue will be investigated in the next section.

3.4 Abrasion Tests

The abrasion can be simulated in different ways. An intensive way to simulate abrasion is to use a sand storm simulator acc. IEC 60086-2-68 [2]. Results of these tests show an abrasion on the glass surface resulting in a loss of transmission. [10] Another possibility is to make accelerated abrasion tests with the cleaning system, which will be used to clean the modules regularly. But this limits the expressiveness of the tests due to the effect that no comparability is given and only the specific combination of cleaning device and module to be cleaned can be studied and evaluated. Another favorable way could be the utilization of the abrasion test acc. EN 1096-2:2012 for coated glasses[3]. This standard suggests to abrade the coated glass with an abrasion felt in 500 strokes in a combined linear and rotating movement. The pass criteria for the test is a transmission loss of <0.05. Beside this standard procedure three abradants were evaluated as well as different stroke cycles. The experiment was performed on commercially available glasses of two producers with a sputtered ARC (A) and a roller coated ARC (B). In section 2.3 to 2.6 one can find more details about the testing procedures

Figure 9 shows the results in an overview plot. On the ordinate one can see the variation of stroke cycles (50, 100, 250 and 1000) and on the abscissa the four different abrasion materials (AF ... abrasion felt, and three abradants differing in its hardness: CS17 elastic hard, CS10 elastic soft and CS10F elastic extreme soft). The z-axis (in top view) shows the results of the abrasion expressed by the quotient resulting from the final transmission measurement and the reference. At a first glance one can conclude - as already anticipated - that the sputtered ARC has an higher abrasion resistance than the roller-coated. The maximum abrasion for the sputtered ARC is $\Delta\tau_e$ = 1.62 ± 0.26 % for 1000 stroke cycles and CS10 (elastic soft). The more damageable roller-coated ARC has a maximum abrasion of $\Delta\tau_e$ = 2.48 ± 0.26 % for 1000 stroke cycles and CS10F (elastic extreme soft).

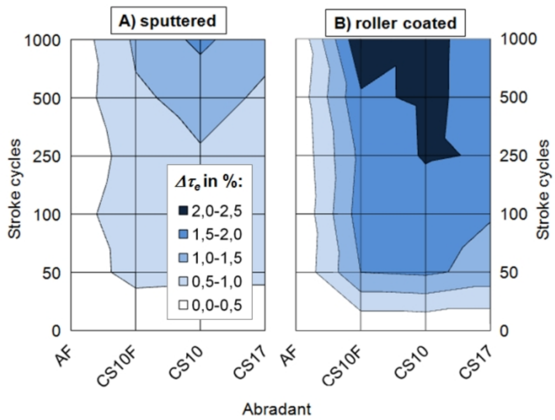

Figure 9: Abrasion effect ($\tau_{e,initial}/\tau_{e,final}$) in % investigated on a sputtered (A) and a roller coated (B) ARC. The experiment was performed under a variation of number of stroke cycles and the hardness of the abradants. Additionally an abrasion felt was investigated

The test conditions in the standard are 500 strokes, with a force of 4 N on the ARC abraded with an abrasion felt. To meet the requirement of the standard the transmission loss has to be smaller than 5%. In the results of figure 9 one can see under these conditions no countable effect. 1000 strokes with the toughest abradant results in a maximum transmission loss of -2.5 %, which is considerably lower than the requirement. We suggest to lower the criteria to 2.5 %

3.5 Automated dust cleaning solutions

In some areas of the world natural cleaning is very limited due to limited water resources (rain or usable water from earth). Mani et.al. suggest cleaning cycles depending on a climatic zone. The advised schedules go from daily, over weekly or biweekly to event dependent cleaning, like a sand storm or snow fall. This does not claim to be complete, for further details see [5]. If it is not possible to clean with water one way to clean is using automated brush-cleaning systems. Some of these systems were installed in Israel were it is necessary to clean in daily or even twice a day cycles due to the permanent deposition of sand and dust.

PI-Berlin was requested to evaluate some of these systems in terms of the influence of the cleaning process in terms of module quality. The intention for the tests is to figure out the long-term influence of the cleaning device in terms of module power and yield by measureable damages and not cleaning improvement. Figure 10 shows an example of an automated cleaning system [9]. A special test procedure was designed to evaluate a cleaning life-cycle "stress" to some common module types. Initial measurements of visual inspection, power measurements, electroluminescence and reflection were performed. The stress test was simulated under real conditions (same construction, regular sand deposition of same sand type) with cycle numbers, which correspond to all cleaning cycles of a regular modules life-time.

Figure 10: Mitigation as dust cleaning solution in an automated brush-cleaning system in Israel [9]

The results of the performed simulated long-term cleaning test show that the modules are not damaged. None of the modules tested was influenced in its power or a countable damage in electroluminescence. Only a few modules show an optical change of its glass surface, which indicates a change in the reflection. Investigations with reflection measurements are currently going on.

4 CONCLUSION

The soiling behaviour of a module is strongly depending from the environmental condition of a specific location. It depends on surface morphology and tilt angle. Prismatic and pyramid structured glasses soil easier especially under flat angles in flat-roof integrated systems or equatorial regions.

Anti-soiling-coatings can help improving the self-cleaning properties and therefore improve the yield of a PV system. To investigate self-cleaning properties of surfaces a test method and test equipment was presented.

The abrasion on coatings due to soil or cleaning devices can be investigated by an abrasion test. The test enable to investigate the long time reliability on coatings.

5 ACKNOWLEDGEMENTS

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