How soiling and cleaning impact module performance in deserts

Module cleaning | In recent years the number of PV installations in desert regions has increased, and regular cleaning of the modules in these areas is necessary because of energy yield losses due to soiling. Investigations carried out by Nicoletta Ferretti and Juliane Berghold at PI Berlin, however, suggest that the stress caused by the cleaning procedure employed potentially affects the module performance during its lifetime.

For most commercial PV modules, anti-reflection coatings (ARCs) are deposited on the glass surface in order to enhance the angular transmission of the incident light, thus improving the module energy yield, in particular at grazing angles of incident radiation [1–4]. Even if the modules with these coatings initially demonstrate better performance [5], the ARC may degrade because of faster abrasion in desert regions, where they are occasionally exposed to sandstorms. Moreover, the cleaning method used (including specific brushes, etc.) might additionally accelerate the degradation of the coatings.

Soiling tests were performed at the PI Photovoltaik-Institut Berlin (PI Berlin) in order to investigate the effect of soiling on the performance of different modules and determine the self-cleaning properties of the coatings. The impact of commercial cleaning devices on the modules was also analysed by carrying out accelerated cleaning tests. These cleaning devices were tested on the module types installed in a specific power plant, and a number of cleaning cycles corresponding to a defined number of years of operation were completed.

The cleaning frequency and the soiling simulation were specific to the location. Visual inspections, performance measurements under standard test conditions (STC), and electroluminescence and reflectance measurements were performed before and after the accelerated cleaning procedures. The degradation of the ARC in particular was analysed, because, as it turned out, this was the major problem. The tests also made it possible to compare different ARCs, and investigate, through reflection measurements, how the ARCs were affected by the abrasion caused by cleaning.

> "The ARC may degrade because of faster abrasion in desert regions"

Field results

PI Berlin performed a quality inspection of a 40MW power plant in a desert region in Israel, which had been connected to the grid a few days before. Sand covering the modules had accumulated over the few months of the installation period. Performance and electroluminescence measurements were taken at thirteen evenly distributed locations around the PV plant.

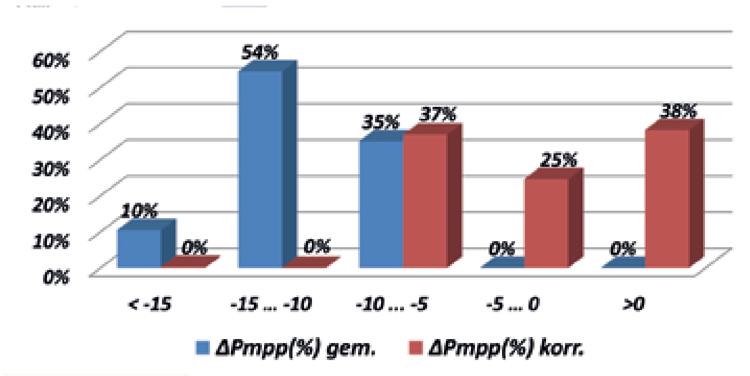
An infrared inspection of the entire plant was also carried out: hot-spot issues caused by soiling and generated within a few days of the grid connection were detected in 150 modules. Even more modules showed a local temperature increase, indicating a significant hot-spot risk.

Additionally, module power was measured before and after cleaning (see Fig. 1) of the modules from the plant. Power losses of up to 28% were detected, and all the modules measured with this method showed losses greater than 5% of nominal values; however, the power loss was mainly because of the soiling. When the differences due to soiling were discounted from the power of the modules of each group, 63% of the modules did not demonstrate power losses greater than 5% (see Fig. 2).

Soiling test

The effect of soiling on module power, and the self-cleaning properties of coated glasses, were investigated in the laboratory by adapting the test described in the standard EN 1096-5 ('Glass in building

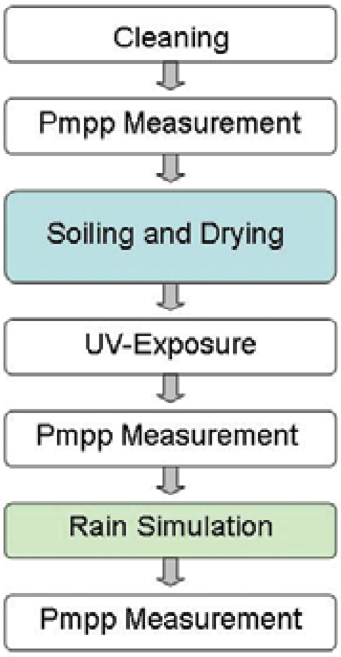
▼Figure 1. Reference module for measuring soiling losses in the plant.



◀ **Figure 2. Measured maximum power deviation from the nominal value (blue) and after correction for soiling losses (red).**

◀ **Table 1. Maximum power and reflectance deviations (after cleaning with respect to initial values) for the five modules tested with cleaning device 1.**

Producer	Simulation period [years]	ΔP_{mpp} [%]	Δ reflectance [%]	Result
A	20	−0.3	25.0	Pass
B	20	−0.6	18.1	Pass
C	20	+0.1	1.1	Pass
D	20	−0.9	62.8	Fail
E	20	−0.9	1.4	Pass



▶ **Figure 3. Procedure for testing the self-cleaning properties of coated glasses.**

– Coated glass’). Unlike in the standard, the angle at which the dirt solution was sprayed onto the modules was variable. The substances included in the solution were in accordance with the specifications of the standard and consisted of soluble salts and non-soluble components in an acid solution. The method used is illustrated in Fig. 3.

By means of the soiling test, it is possible to compare two different anti-soiling coatings – ASC1 and ASC2 – on standard microcrystalline silicon (μc-Si) modules. In Fig. 4 the results of the inclined irradiation behaviour of ASC2 coating vs. the radiation angle *α* are plotted; the latter is equal to zero when the radiation is perpendicular to the front side of the module. It can be observed that after soiling, for incident radiation angles greater than 40° the normalised short-circuit current given by

$$I_{sc,norm} = \frac{I_{sc}}{I_{sc}(0) \times \cos(\alpha)} \qquad (1)$$

is less than the initial values. This means that the effects of soiling on module performance are stronger at grazing angles of incident radiation.

The ASC2 coating showed better self-cleaning properties than ASC1, as after the rain test the results were close to the initial ones. The maximum power measured under STC after rain for the module with ASC2 was 5% higher than for the module with ASC1. The two modules with coatings and one μc-Si-module were installed outdoors for 10 days and the power was recorded. The module with ASC2 produced 2.8% higher specific energy yield than the reference module, while the yield was 1.8% higher for the module with ASC1; this indicates that the anti-reflection properties of ASC2 are better.

Accelerated cleaning

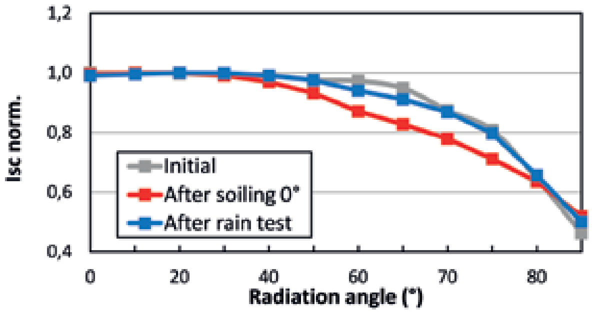
Several commercial cleaning solutions are currently available on the market and can be used either dry or with water. At PI Berlin the impact of the cleaning devices on the PV modules is tested by performing an accelerated stress test, with the aim of simulating a defined number of years of operation of the cleaning device in a specific power plant. The devices are tested in relation to the module types installed. The number of cleaning cycles to be conducted in the accelerated test depends on the number of years of operation to be simulated. Soiling effects are also simulated by spreading out sand on the modules; the frequency at which this is done depends on the field conditions.

To investigate the effect of the cleaning, the module types under study are characterised before and after the treatment. Visual inspections, performance measurements under STC, and electroluminescence and reflectance measurements are performed. With an electroluminescence analysis, module abnormalities at the cell level that have been caused by stress tests can be identified. The PI Berlin internal requirement for passing the reflection test is that the deviation after the stress test with respect to the initial measurement must be less than 30%.

A particular focus of the investigations is the impact of the cleaning treatment on the module’s ARC; the effect is correlated with the module reflectance. In relation to the resulting impact on the modules, improvements to the cleaning devices can then be recommended to the producers.

In the work reported in this paper, the impacts of two different commercial cleaning devices on the lifetimes of several module types were investigated. The first device is manually driven and operates with water; the modules are cleaned by brushes attached to a profile which rolls along the module frame. The second device is an automatic robot which performs a dry cleaning; microfibre material fixed to an independent profile rotates over the tested modules. The impacts on the modules cleaned using the two different devices were compared.

▼ **Figure 4. Inclined irradiation behaviour of the module with ASC2, as a function of the radiation angle.**



Cleaning device 1

For the first cleaning device, modules from five different producers were tested. The results for the maximum power and averaged reflection deviations (after cleaning with respect to initial values) are summarised in Table 1. For all five investigated module types, no significant change in performance at STC was detected after the cleaning test.

In order to investigate the effect of removal of the ARC by cleaning, the modules had to be installed outdoors to measure specific energy yields, as the coating is more effective with inclined incident radiation. No significant deviation was observed by electroluminescence.

For the modules from producers A and B, a minor increase in module reflectance was detected after the stress test; this also correlates with the slight striping observed on the front glass after the cleaning. For the module from producer D, however, a significant impact on the reflectance was noticed, indicating a removal of the coating, which also correlates with clearly visible striping on the front glass after the cleaning test. The observed increase in reflectance of this module was higher than the acceptance criterion of PI Berlin for a pass (less than 30%).

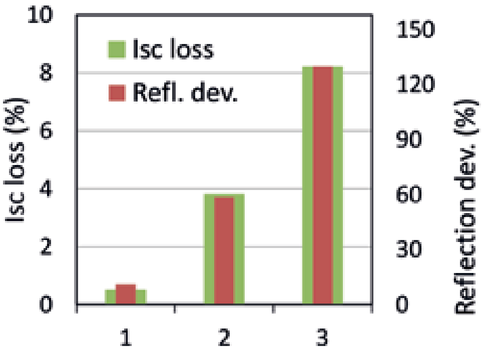
The first cleaning device was subsequently improved by the installation of softer brushes, and the accelerated test repeated for this specific module. With the new brushes, after a simulated cleaning of 20 years the reflectance deviation was only 6.5%, signifying a test pass.

Cleaning device 2

For the second cleaning device (a cleaning robot with dry cleaning), one module from producer F was tested by simulating 20 years of operation; accordingly, the cleaning motion, impact and speed of the microfibre elements, as well as the impact of dust, were simulated with this set-up.

With the particular module type under investigation, a significant deviation in reflectance of 49% was detected; the observed increase in reflectance of this module type exceeds the acceptance criterion from PI Berlin, resulting in a test failure. No significant changes in performance under STC and in electroluminescence, however, were detected after the cleaning test; moreover, the module did not exhibit any visible changes.

The same cleaning device was then tested on another module type (producer G), but with a reduced simulation time in order to focus on the impact of the cleaning procedure on the ARC. Operation periods corresponding to one month, one year and two years of daily cleaning were simulated for three modules. In this case the modules showed no important deviations in performance or reflectance; indeed, the increase in reflectance was well inside PI Berlin's acceptance test criterion of 30%. In addition, the electroluminescence measurements indicated that the module cells did not receive any damage from the cleaning. The modules did not show any particular visual damage either.



▲**Figure 5. Short-circuit current and reflectance deviations for the modules from producer G after the manual cleaning procedure.**

◀**Table 2. Maximum power and reflectance deviations (after cleaning with respect to initial values) for the two modules exposed to manual cleaning.**

Producer	Simulation period [years]	ΔP_{mpp} [%]	Δ reflectance [%]	Result
G	2	–4.3	58.8	Fail
G	4	–8.8	129.9	Fail

▼**Figure 6. Dry cleaning on the lower glass area.**

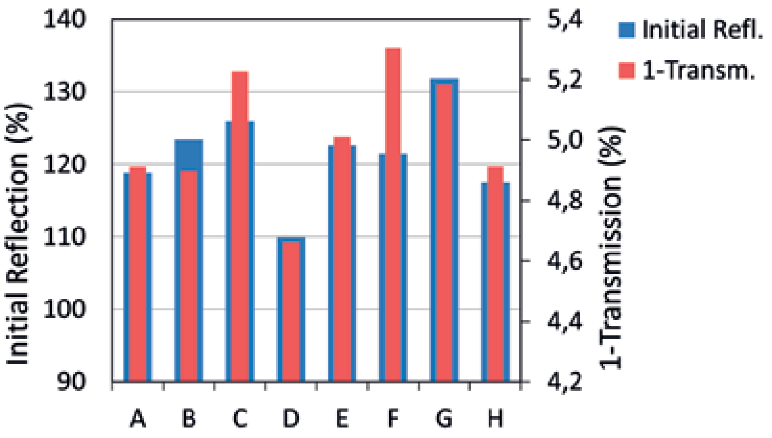
Cleaning method comparison

Another two modules from producer G were manually cleaned for comparison purposes. An accelerated testing for a simulation of two years of manual cleaning was applied to one module, and a simulation of four years to the other module. In this case, the dust spread on the modules was dampened and dried before each cleaning.

The electroluminescence measurements indicated that the module cells did not receive any damage from the manual cleaning; however, both the performance and the reflectance measurements showed large deviations for the modules that were manually cleaned (see Table 2 and Fig. 5). In particular, strong deviations could be observed after the simulation of four years of operation; the glass surface was also visibly damaged and had become more opaque at the edges.

> "The manual cleaning procedure went beyond removing the ARC: it also scratched the glass surface"

In Figure 5 it can be observed that the power and reflection deviations follow a similar trend; this effect can be attributed to the fact that for these modules the sand was dried on the modules before the manual cleaning. As could be seen



◀ Figure 7. Initial reflection averaged over the eight initial measurements (left axis). Values for '1–transmission' resulting from the I_{sc} measurements of modules with the glasses in front (right axis).

by visual inspection, the manual cleaning procedure went beyond removing the ARC: it also scratched the glass surface, thus reducing the normal transmission of the glass.

Comparison of different ARCs

Eight different ARCs on slightly textured solar glasses were compared in respect of durability. For this purpose, reflection measurements were performed before and after abrasion and cleaning tests. The goal was to check the effects of the stress tests on the ARCs, and to evaluate how fast the coatings were removed by cleaning in comparison to abrasion.

Glass abrasion was performed on the upper glass area for 25, 50, 250, 500 and 1,000 cycles. On the lower area of the same glass, dry cleaning was conducted for 100, 500 and 1,000 cycles. The abrasion test was carried out using a TABER Linear Abraser 364 in accordance with the EN 1096-2:2012 norm. The cleaning set-up used for the testing is shown in Fig. 6.

Initial reflection measurements were taken at eight positions and then averaged. The initial measurements showed significant differences between the different glass types; the higher the reflection, the worse the anti-reflection properties of a specific coating.

The glasses were placed in front of a crystalline module, and *I–V* curve measurements under STC were then taken. The I_{sc} resulting from the measurements with the glass in front divided by the current of the module without glass is considered to be the glass transmission. In Fig. 7 the values for '1–transmission' (reflection + transmission = 1 if the absorption is close to zero) are plotted together with the initial reflection: the trend is similar for most of the glasses.

In contrast to when the modules were measured after cleaning, here the effect of the coating is detected by performance measurements under STC; the reason for this is the structure of the glasses, which collect the incident irradiation at an inclined angle.

After abrasion exposure, it can be seen that the reflection gain is not linear with the cycle number (Fig. 8). The gain is greater at the beginning and tends to 'stabilise' after a certain number of cycles, indicating that the ARC has been completely removed. For most of the producers, the coating can be considered to be removed after 250 cycles (see also Fig. 9). Only with the producer D glass does the reflectivity show a distinct increase after 1,000 cycles; in this case the ARC cannot be considered to have been completely removed. Fig. 9 clearly shows the large variation between different producers in terms of the reflection deviation after 25 cycles.

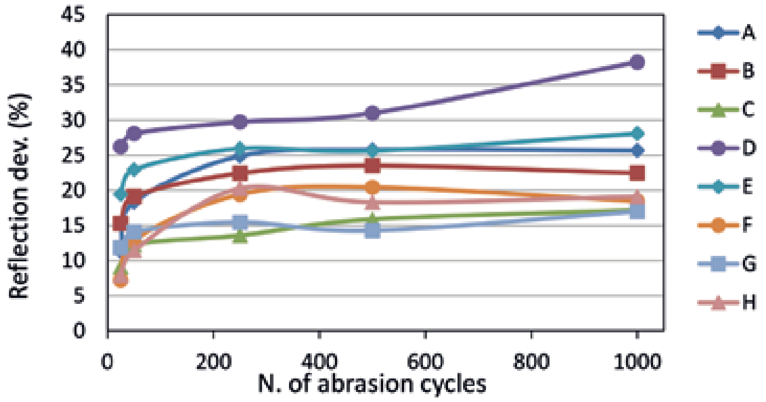
Dry cleaning was performed on the lower area of the glasses for 100, 500 and 1,000 cycles (each cycle corresponds to one back and forth movement). The final reflection deviations with respect to initial values are plotted in Fig. 10: it can be observed that after 1,000 dry-cleaning cycles, the reflection deviations are still smaller than after 25 abrasion cycles.

Table 3 presents a summary of the evaluation and benchmarking for the different solar glasses with respect to the initial anti-reflection properties and the durability of the relevant coatings. The initial anti-reflection properties are evaluated as 'good' (1=best) when the initial reflection is low. The abrasion durability is evaluated by considering the deviation in averaged reflection between 1,000 and 25 cycles.

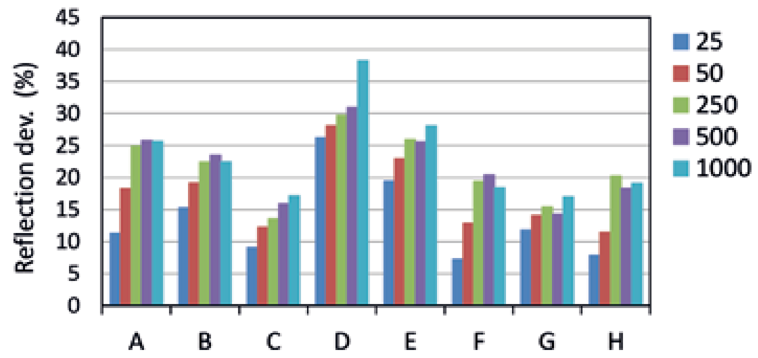
The cleaning resistivity is evaluated by considering the gain in reflection after 1,000 cycles of cleaning. (Only in the case of producer E was the value after 500 cycles considered.) After the 'mechanical'

Producer	Anti-reflection	Abrasion durability	Cleaning resistivity
A	3	3	8
B	6	5	7
C	7	4	2
D	1	6	4
E	5	7	6
F	4	1	3
G	8	8	5
H	2	2	1

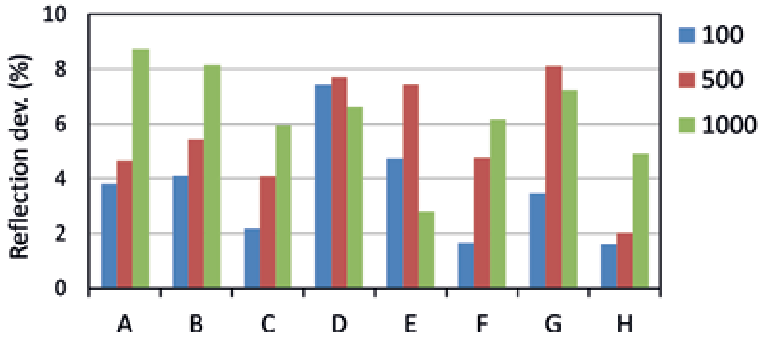
◀ Table 3. Anti-reflection properties and durability evaluation (1 = best, 8 = worst).



◀ Figure 8. Reflection deviations after abrasion exposure with respect to initial values, for different numbers of cycles.



◀ **Figure 9. Reflection deviations after abrasion exposure with respect to initial values, for different glass producers.**



◀ **Figure 10. Reflection deviations after 100, 500 and 1,000 cycles of dry cleaning with respect to initial values, for different glass producers.**

exposure, the smaller the gain in reflection, the more resistant the ARC to abrasion (1 = best).

When anti-reflection properties, abrasion durability and cleaning resistivity are all taken into consideration, it can be concluded that the best-performing glass type is the one from producer H. The ARC of this glass type can be regarded as mechanically resistant, with a complete removal occurring after 250 abrasion cycles, corresponding to a 20% gain in reflection (with respect to initial). In terms of cleaning, 1,000 cycles would correspond to a gain in reflection of only around 5%, which equates to a removal of about 25% of the coating.

> "The impact of a cleaning device should be tested by considering the soiling conditions and the cleaning frequency specific to a particular PV plant"

In contrast, for the D producer, a gain in reflection of approximately 7% was observed after 1,000 cleaning cycles. In order to determine at which stage the ARC is removed, however, more abrasion cycles would need to be performed until the reflection has stabilised.

Conclusions

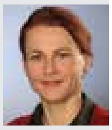
In the work reported here, the impact of accelerated cleaning on several modules from different producers was investigated. Electroluminescence measurements showed no important deviations after the stress test with respect to the initial measurements, indicating that no damage had occurred to the module cells. Reflection measurements showed that both of the cleaning devices tested affected the ARCs of some types of module. Performance measurements under STC did not reveal any significant changes as a result of the cleaning with the commercial devices. The impact on module performance was not detectable under STC measurements, because the ARC is more effective at inclined angles of incident radiation [6].

From the simulation of a monthly manual cleaning, significant deviations in reflection and performance were measured, attributable to a scratching of the glass surface. The different coatings on slightly textured glasses were shown to have different impacts on module performance under STC. In this case, the structure of the glass allows the detection of changes in performance for an incident radiation perpendicular to the module too. With regard to abrasion, the glasses demonstrated different resistivities; the ARC of glass D, with the best initial anti-reflection properties, showed the highest reflection deviation after 25 abrasion cycles.

The reflectivity of most of the glasses stabilised after 250 abrasion cycles, indicating a complete removal of the ARC. After 1,000 cycles of dry cleaning, the reflectivity showed much smaller deviations than after abrasion testing; none of the glasses reached a stable state after cleaning cycles. The impact of a cleaning device on a certain module type should therefore be tested by considering the soiling conditions and the cleaning frequency specific to a particular PV plant. ■

Authors

Nicoletta Ferretti studied physics at the University of Bologna and completed her Ph.D. at Helmholtz-Zentrum Berlin in 2008. She now works at PI Berlin as a research associate in the R&D department, where her main focus is on methods for determining module power.



Juliane Berghold received her Ph.D. in physical chemistry in 2006 from Freie Universität Berlin. She has more than 15 years' experience in PV technology, including R&D, consultancy and management. She currently heads the PV module technology and R&D services business unit at PI Berlin.

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