Advances in self-cleaning PV module technologies – a review

Module performance | Technologies purporting to alleviate performance losses in PV modules due to soiling from dust and other airborne particles are becoming more widely available. But do they work? Elisabeth Klimm and Karl-Anders Weiß of Fraunhofer ISE investigate

Soiling impact on PV module performance

A reduction of light transmission through the glazing of a PV module by solid airborne particles settling and forming a layer, can cause up to an 80% performance loss within four months [1] if relevant climatic effects, e.g. dry surrounding with wind, humidity and salt, are combined in a negative way at one position (Figure 1). In addition, it has been shown that soiling layers can also support additional degradation such as corrosion or potential-induced degradation (PID) of sensitive module types [2].

The soiling effect and its severity are extremely location dependent and can differ even within some 100 metres or some kilometres. Some general terms relevant for the soiling phenomena are deposition, accumulation, soiling loss, soiling ratio and soiling rate. *Deposition* describes the amount of sedimentation onto a surface in a time and *accumulation* describes the sediment that remains at a surface. Figure 2 shows the processes of dust uptake, transport and deposition. The three mechanisms by which the particles are deposited are I) random Brownian movement II) turbulent deposition or inertia and III) sedimentation by gravitational forces. The random Brownian movement is induced by the constant interaction of dust particles with the surrounding molecules of the air thus also being the predominant deposition mechanism for small particles of <1μm in diameter [3]. Turbulent deposition occurs when the particle has enough energy to trespass into the laminar boundary layer. The deposition of larger particles (>100 μm) is forced by sedimentation. After deposition, particles may adhere to the surface and accumulate as an effect of the following adhesion forces acting on the particle I) Van der Waals II) capillary forces and III) electrostatic forces. The capillary forces become only of importance when water molecules in significant amount disconnect the dust particle from the solar glass surface. Until then the short range Van der Waals and electrostatic forces are the dominant forces for the particle-surface interaction [4].

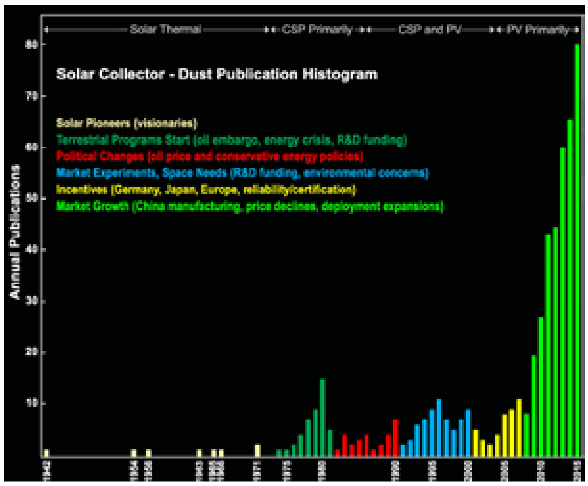


Figure 3. Overview of soiling studies [7]

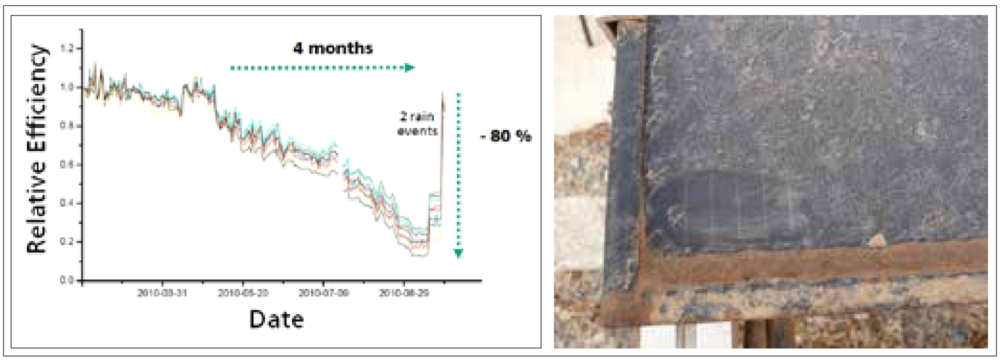


Figure 1. Efficiency loss of 80 % within four months after outdoor exposure of test modules at the ITC test site in Gran Canaria, Spain

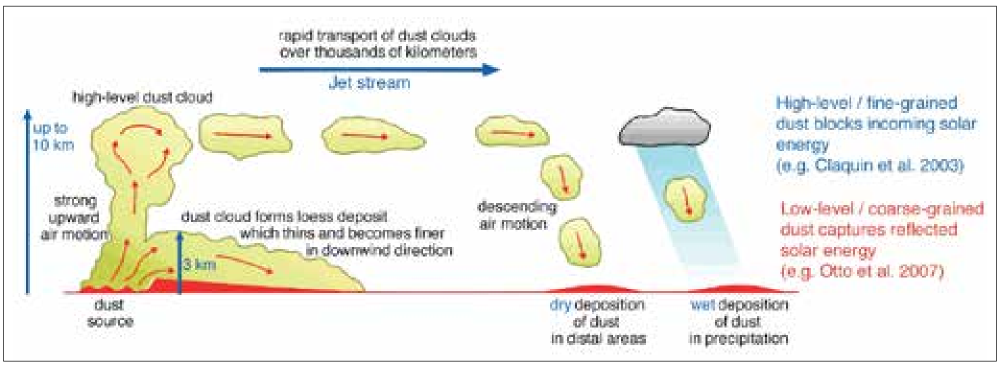


Figure 2. Schematic diagram showing different dust transport mechanisms in the high and low level atmosphere (Stuut and Prins, 2014, redrawn from Pye and Zhou, 1989)

Other important terms are the *soiling loss*, which describes the yield loss of PV modules due to particle accumulation. Again, this is location dependent and can account for 0 up to 2% per day [5]. Kipp & Zonen B.V. reported on power losses within one week of >10%. The last terms to be defined are the *soiling ratio*, which is the measured ratio of dirty to clean at a given point, and the *soiling rate*, which describes the average soiling loss per unit period of time. Research of the soiling phenomenon also requires the understanding of the dust sources, transport and sinks.

Although the topic has been getting lots of attention during recent years by the remarkable number of researchers active in this field (see Figure 3), further research has to be carried out, taking into account site-specific impacts and multiple variables in order to provide suitable mitigation approaches.

Soiling effects

Degradation of PV power plants is mainly induced extrinsically by exposure to local atmospheric and climatic conditions. This situation is of special severity in arid zones due to the usually high irradiance, big temperature cycles and high peak temperatures. In addition one major location-dependent factor reducing the efficiency of PV power plants is soiling. Soiling is defined as the deposition and accumulation of contaminants in general particulate matter on surfaces, in arid zones mainly mineral dust (< 63 µm) and sand grains, of the PV modules [6]. The relationship between the loss of efficiency and soiling depends on the characteristics of the dust particles and the dust layer on top of the module surface. The physical and chemical characteristics include the particle size distribution, the particle shape, the chemical composition, the particle-surface interaction and the soiling rate itself. These factors are influenced by the climate and location around the power plant, but also by the installation itself – for example, tilt angle – and can be altered by the exposed PV module surface, (Fig. 4)

A correlation of the soiling layer mass and the transmittance loss, which is dependent on the type of dust, is found [7]. It varies with the location because different types of dust have different effects on the transmittance loss (Graph 1), what we call the soiling effectivity of dust. Finer dust particles induce larger losses because of the higher layer density with larger effective superficial area. The particle shape, colour and chemical composition also influence the light absorption or scattering at the surface. In certain conditions the soiling mass even relates in a linear way with the power loss of the PV modules. For the soiling layer in dry conditions sigmoidal growth up to a certain threshold has also been found experimentally, whereas a layer under humid conditions can grow thicker and more packed, lowering the transmittance further.

The soiling phenomenon is governed by the interaction of several forces – gravity force, drag force and adhesion forces – where drag and adhesion forces determine the total amount of initial dust deposition. Hence the characteristics of the soiling effect and the effort to clean the surface are set by dry deposition and ambient conditions and also influence the plant specific levelised costs of electricity (LCOE) significantly.

In the last decade, PV module prices have fallen from about €2.7/WP to about €0.6/WP, and accordingly, the global PV market has grown significantly. In 2016, the increase was over 30% and cumulatively one third of a terawatt of PV capacity was installed globally by the end of 2016. PV is booming and will continue to grow rapidly [8]. Just recently it was announced that the Kingdom of Saudi Arabia will install 41GWP of solar systems in the next 20 years. There are more renewable energy projects in the Gulf states at the planning and installation stages, such as Kuwait's Shagaya Multi-Renewable Energy Park Project with 10MWP PV or Dubai's Clean Energy Initiative with 4GWP of PV, and the "Shams Dubai" Programme being the largest solar project in Middle East, planning to install solar PV on every rooftop by 2030. The Middle East and North Africa (MENA) region has high solar potential and the spatial capability, but the extreme climate conditions make it difficult to adapt the technology. Soiling research is of interest for all solar technologies targeting dry and arid, sunny regions with the key themes on: I) performance with harsh soiling II) dust and adhesion mechanism III) standards and coatings IV) soiling loss measurements and predictive modelling and V) cleaning and robots and O&M in general.

Adapting solar technology to dry and hot desert climates is a key factor, since the location of a solar system plays a significant role in the reliability and soiling mitigation. Often sites with high solar radiation are characterised by low humidity and rare rain events [9] as well as the influence of sand and sandstorms. Studies tend to compare soiling losses from different climates, especially tropical versus arid regions, despite the fact that in different climates, different soiling mechanisms are present and different mitigation measures are most likely to be taken. Green solar surfaces caused by biological soiling films, combined with biomass and black carbon, are found in tropical areas with rural or

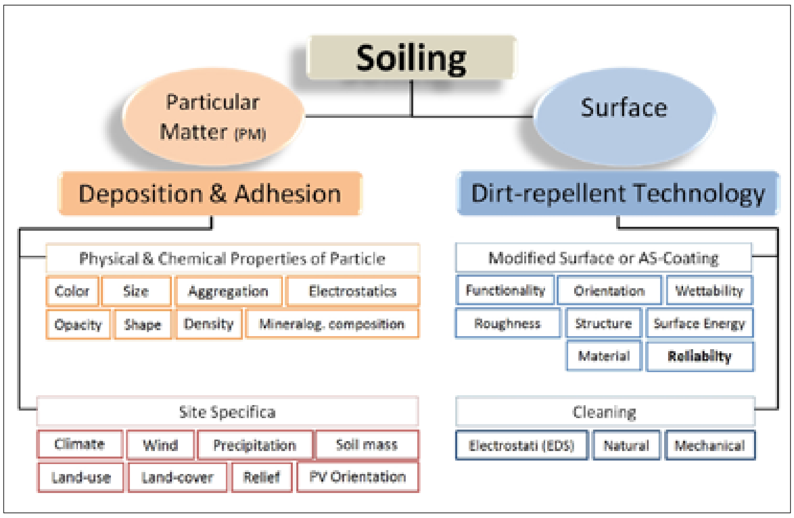
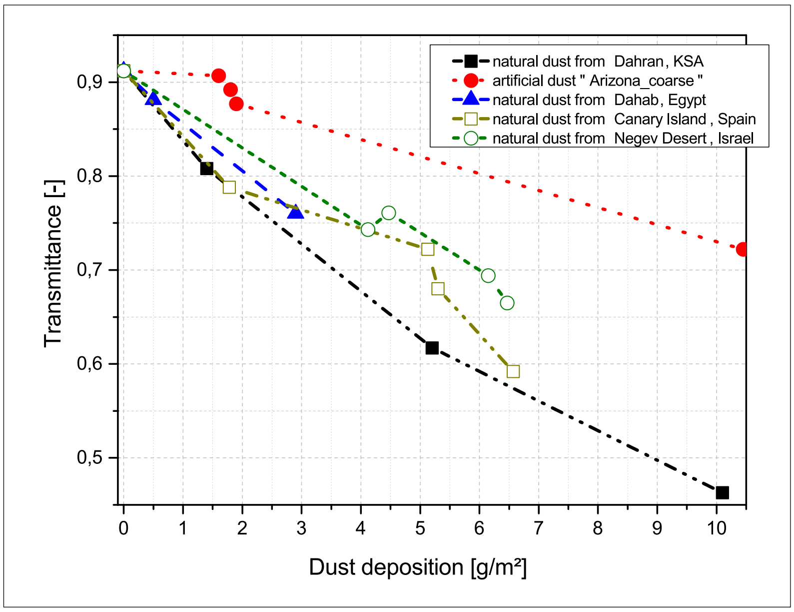


Figure 4. Factors influencing soiling



Graph 1. Correlation of soiling layer mass and transmittance, in dependency of dust type, Klimm et al., 2015, Proceedings of IEEE 42th PV SC

urban land use. Whereas in dry regions, with an arid climate or arid with maritime conditions, the deposition consists mainly of mineral dust, possibly combined with salts.

In scientific publications case studies describe the soiling loss in % per day only within the own climatic conditions, e.g. tropical climate. A summary of eight recent cases of solar systems in tropical climates gives an average loss of 0.39% per day; but also up to 1% loss per day. Meanwhile, 31 recent case studies on solar systems in arid climates show an average loss of 0.46% per day and up to 1.1% per day. Both climates are of course more affected by soiling than regions with a moderate climate. Not many publications have focused on the yield loss by surface coverage from snow and ice in the cold climate so far. There are many studies on soiling effects presented currently, but few can be compared in detail because of different boundary conditions. Since factors such as precipitation intensity and wind speed vary with the change of seasons, soiling-related power loss is inhomogeneous within one year. In general, the performance degradation is higher during the dry seasons (e.g. dry summer in the MENA region) and consequently lower during the wet or rainy seasons (arid and tropic climate).

Self-cleaning methods and technologies for PV panels

Soiling mitigation or anti-soiling methods exist to reduce the impact of deposited dust and cementation, the worst case of soiling. Basically there are two distinct concepts for the dust resistant glazing: self-cleaning surfaces and active cleaning by electric fields, Fig. 5, [10].

To clarify, there are no known surfaces and coatings to completely prevent dust deposition or adhesion. So-called "self-cleaning" coatings are available to help the natural processes without the use of external water, brushes or power to remove soil particles, but do not yet do the cleaning on their own. This means that "self-cleaning" is usually a marketing term but not a reality (yet). To help these self-cleaners there are some R&D approaches to cleaning, including the heating of PV modules or cooling the PV modules to prevent or induce dew formation. Dew has been shown to accelerate or worsen soiling (cementation) and makes cleaning more difficult, but can also aid cleaning depending on the amount of dew and properties of the dust particles. Now artificially inducing dew and making it work will require energy, which reduces the "self-cleaning" capabilities of the coatings and also their economic and ecologic attractiveness. Meanwhile water, in terms of stronger natural rain or active cleaning with water and brushes, has also been shown to wash off the soiling layer. Wind has also shown to clean the modules, if strong enough, so that the aerodynamic force and dynamic torque of the wind exceed the adhesion forces to the surface and detach the particle from the surface [11].On other hand dew, water and wind are loads for the functional dirt-repellent coating, which can stress it in terms of corrosion and abrasion.

In general, mitigation and cleaning techniques are targeted in a passive or active way. The active cleaning methods can be supported by passive functional "self-cleaning" surfaces, received i.e. by surface modification, by varying the structures or the surface energy. To help remove the soiling layer functional coatings may be applied. The basic principle of these "anti-soiling" (AS) coatings is to lower or increase the surface energy of the solar glass by applying hydrophilic or hydrophobic structures, Fig. 5. Superhydrophobic structures are known from the "lotus effect" based on nano-structures preventing the wetting of surfaces. Water will form droplets on the surface, which pick up dust when they roll down an inclined module. Furthermore, the contact area of the water but also of the dust particles is minimised if the surface patterning is below the mean dust particle size. Thereby, adhesion of the particles is decreased. Hydrophobic surfaces can be achieved either by chemical modification to minimise surface energy or by the use of micro- or nano-structures. Moreover, these structured surfaces act as an anti-reflection cover and thus enhance the light transmission of the module glazing. However, in this application abrasion resistance as well as optical properties of this texture have to be considered.

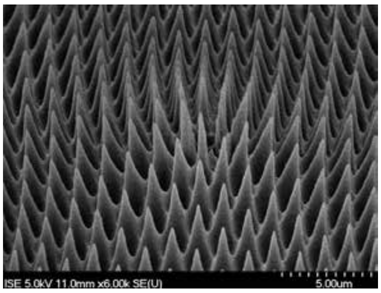


Figure 6. SEM Image of a super-hydrophobic surface [15]

Hydrophilic coatings, meanwhile, have been successfully used for decades in self-cleaning architectural glass. Superhydrophilic coatings ensure an excellent wetting and contaminants can be easily rinsed off. However, also in the absence of rain a self-cleaning effect was reported. Hydrophobic coatings are mainly made of inorganic TiOx or SiOx and hydrophillic coatings are mainly made of silicones or fluoropolymers. TiOx has an additional advantage of being photocatalytic, using the incident light to decompose organics, but on the other side decreases the overall transmittance of the solar glazing. Newer developments include a combination of hydrophilic and hydrophobic structures, promising advantages of both technologies. Of course the other properties such as good adherence to the substrate, easy and cost-efficient application, high transparency in the relevant range of solar glass (≥92% transmittance) as well as long-term stability against UV and other environmental degradation factors, as well as abrasion due to sand and cleaning, are to be considered.

Another interesting technology development, albeit one not yet proven on full-sized PV modules, is the so-called electrodynamic screen (EDS), which cleans the solar panel with electrostatic forces. This active, energy-consuming, mitigation technique removes the soiling particle by using the charge of particles. Parallel electrode embedded in the substrate – i.e. solar glass, in the case of modules – can move soiling particles towards the edge of the PV module [12]. It can also support the natural cleaning because once the particles come loose and start hopping, air drag will enhance the cleaning effect. Challenges are right now the transmittance loss due to the electrodes themselves and the design of the parallel electrodes. A fundamental requirement for the electrodes spacing derives from the particle size. Efficient cleaning has been shown for particles

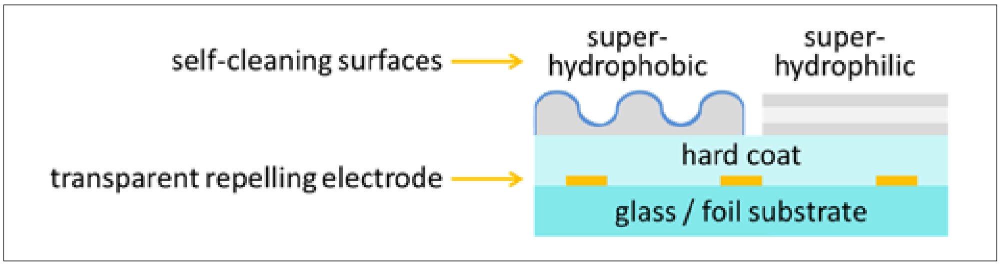


Figure 5. Schematic drawing of the two concepts for dust-resistant glazing with a dust-repelling electrode and the self-cleaning top layers

diameters in the range of the electrode spacing. For larger dust particle diameters, the accelerating force drops rapidly. Therefore, the electrode spacing should be chosen wisely to encompass the major part of the dust particle distribution. From existing literature, the maximum size of dust particles found in desert regions is typically between 50-200 µm [Sarv13]. The exact electrode spacing has to be adjusted according to the selected PV module exposure site. The ambient humidity is not to be neglected, because humid air can short-circuit the electrodes faster and increase the adhesion of particles.

Following crucial issues are that existing EDS require high voltages (up to 1-3 kV and higher) [Sarv13], which might have a negative impact on the stability of the PV module materials. Required high voltage generators and cabling drive up the system cost in the field.

In short: there are different approaches to reduce the effort to keep PV modules clean but none of them can really be called "self-cleaning" and many of them have issues with reliability up to now. Approaches are to combine passive methods with active soiling mitigation technologies, such as different cleaning technologies, for example low-water-consuming robots or dry cleaning equipment. Still unclear is the effect of abrasion, especially with tightly attached soiling coverage. It is expected that for the cleaning process of concentrated collector surfaces, which are basically also glass surfaces and so comparable to PV modules, a reduction of 25% of the previous water consumption seems achievable [12]. For the abrasion issues due to cleaning, there are approaches to design and standardise abrasion tests to benchmark and qualify the functional surfaces, for example with linear or a rotary abrasion tests. In terms of design, the tests are derived from a miniaturised car wash test standard. Of course the geometries, contact force or the force of the brush against the sample are to be specified and validated. But so far there are no scientifically validated abrasion testers. Working with dry dust simulates the worst case and in the MENA region, as representative for locations with water shortage, no or little water is used for cleaning, but the PV modules may be cleaned up to every day. Complementary methodologies for cost reduction are also under investigation, such as the reuse and treatment of cleaning water for reduction of water consumption and the improvement of monitoring in the solar fields by soiling sensors or mathematical tools to optimise cleaning cycles.

Qualification of coatings and reliability testing

The materials and surface functionality have to be qualified with real dust with a reliable and meaningful soiling tool and reproducible results. Until now, and out of lack of a standardised and meaningful artificial dust, many researchers use the artificial Arizona test dust (fine or coarse) for soiling simulation. Its use is also given in different standards e.g. in the standard for blowing dust tests for testing electronics under operation, e.g. according to MIL-STD-810G 510.5. In principle the Arizona test dust is specially designed as finer fractioned dust to identify small gaps in electronics packaging and their resistance against fine particle ingress, which can be tracked easily because of the red dust colour and the extreme stickiness, but it is not designed to measure soiling mitigation measures! Tests show that these tests with standardised dust do not correlate with one of the "real soil" samples we used so all the tests done on coatings are meaningless for specific plant sites if the soil is not comparable with the soil used for the tests. The test should include the physical and chemical properties of the different dust types and as well consider the different prevalent climate conditions affecting the adherence of dust to the surface. One important condition could be condensation on the PV module surface occurring during the morning hours when the modules faces and adapts to the clear night sky temperatures while the ambient relative humidity increases up to 90%.

To qualify the surface and particle analytically there are various possibilities. The surface roughness and structures can e.g. be measured in a high resolution nm-range with an atomic force microscope. For a full physical and chemical characterization of the dust are different methods suitable. Microscopic analysis methods are used to determine the particle shape – for example, by scanning electron microscope or with optical microscopy or laser scanning microscope. The latter can also be used to define particle size distribution, which also can be checked with a laser diffraction particle size analyser. The chemical composition can be investigated by applying energy-dispersive X-ray spectroscopy (EDS) just to mention some analytic possibilities. For the reliability tests, climatic chambers are available to qualify the surfaces for long-term stability of their functionality. Limits in reliability can be found with damp-heat testing with 85°C and 85% relative humidity (r.h.) for some hundreds of hours or even more harsh the humidity freeze test with cycling between minus 40°C to plus 80°C and 85% r.h. At some locations temperatures in the minus range are possible to occur even in the desert, e.g. the Atacama Desert in Chile. Moisture between nanostructures or in porous surfaces is found to be delicate in combination with freezing temperatures and harsh on the functionality. Accelerated ageing tests in general have to be carefully chosen to deliver meaningful results. The test design has to include the sensitivities of materials, such as UV for organic coatings for example, as well as location-specific conditions such as salty atmosphere or specific – for example, abrasive – properties of the dust itself.

Effects of mitigation technologies on module performance

Our opinion on the various approaches described is that the additional cost of coatings or EDS must pay off and the technology should be well chosen to fit to the environmental conditions with regard to functionality and reliability. In order to maintain the reliability of such methods and technologies in the most harsh environments, mainly dry deserts with high UV irradiation and little rain, knowledge about the prevalent soil, humidity and dew points should be taken into account. Mapping and global soiling models are not yet sufficient for PV power plant planning due to difference of conditions even within some kilometres. There are interesting approaches with soiling monitoring by sensors (e.g. by Moroni&Partners, UKC DDSolar, Atonometrics, Campbell or Kipp&Zonen), which are supposed to support optimised O&M of PV power plants and enable calculation models to define cleaning cycles. Since the deposition of soil as well as snow on PV modules is mainly non-uniform because of local conditions such as wind and sun and humidity/rains, spatial soiling rates have to be analysed for a well-considered selection of soiling mitigation approaches. A local variability in PV soiling rates is proven.

Right now there is a large community within the PV Quality Assurance Task Force (PV QAT) Task Group 12 with four subgroups analysing and exchanging information on TG 12-1 sensors and monitoring of soiling, TG 12-2 on solutions for cleaning, TG 12-3 antireflective and/or

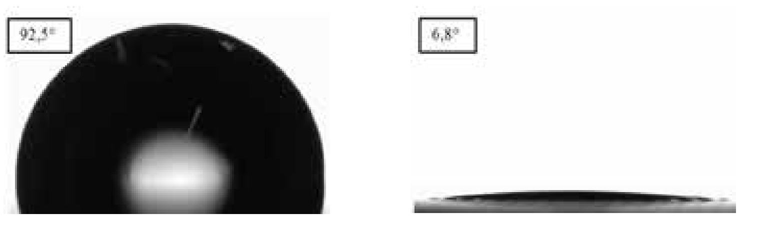


Figure 7. Results of an actual drop contour analysis and the according water contact angle with (left) water droplet on hydrophobic solar glass surface and (right) water layer on hydrophilic solar glass surface [13]

anti-soiling coatings and the TG 12-4 on modelling/analysis of the effects of soiling on PV systems.

Adoption of self-cleaning technologies by the PV industry and future trends

Actual AS hybrid surfaces show an improved cleaning efficiency, but are not self-cleaning and not yet proven to be reliable in the long term. Soiling mechanisms are in our view not yet or never to be standardised, due to the dominating influence of very local conditions and variability even within one PV power plant. In addition soiling affects different PV technologies differently, since soiling induces higher attenuation at shorter wavelengths and a red-shift of the spectral irradiance reaching the active semiconductor.

Newest research insights

In 2018, work at Fraunhofer ISE has been investigating the effect of soiling on the performance of solar systems and evaluating hydrophobic and hydrophilic anti-soiling coatings on solar glass, Fig. 7.

An experimental investigation of the functionality of anti-soiling coatings has been performed, characterising several coated and non-coated glass samples through contact angle measurement and artificial dust deposition. Based on the measurement results, a selection of promising samples has been made for further investigation. The transmittance was measured via FT-IR-spectroscopy before and after soiling the surfaces with artificial test dust. With the goal to develop and optimise a method of quantifying the soiling losses, the soiled glass samples and a clean reference sample were mounted on single-cell PV-modules in the roof top test field in Freiburg, Germany, (Fig. 8) and the modules' power output and backside temperature were constantly monitored. The photovoltaic current is directly related to the transmittance and therefore is used as a sensor to determine transmittance losses. This sensor set up showed satisfying results on the soiling loss and soiling ratio calculations. During the exposure time, several rain events occurred; proving previous findings [14] that rain events with little precipitation (<5 mm, in this case 1mm) are negative for the performance, showing a very inhomogeneous soiling layer. A second rain event (7mm) cleaned off most of the applied dust and recovered the yield.

After leaving each glass sample in the test field for several days, the transmittance was measured again, showing that all the glass samples recovered almost to their initial transmittance. In this study, the glass sample with hydrophobic coating showed the best results in transmittance, followed by the sample with hydrophilic coating. The lowest transmittance was presented by the non-coated glass sample, proving the positive effect of the dirt-repellent coatings.

Furthermore, the cost effectiveness has been calculated, with the payback time surpassing the life expectancy not only of the coatings but also of the modules. It must be noted, however, that the estimated coating prices might be decreasing with increasing market availability of the coatings, leading to a shorter payback time then the calculated or by producers given one. It is also worth noting, that the application might be more cost effective in arid regions, with higher maintenance and cleaning as well as larger effect of soiling losses [13].

We do not want to state that the AS coatings are not helpful but one has to be extremely careful when selecting a coating for a specific site with regard to the local soil and the reliability. The coatings have the potential to significantly reduce the cleaning effort when selected well but can even worsen the situation when selected incorrectly. ■

Figure 8. PV mini module as a soiling-sensor with reference module for the investigation of the impact of dust accumulation on PV performance with monitoring of current, backside temperature, solar radiation; on the right the mini module with the artificial soiled anti-soiling coated glass [13]

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