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SOLAR ASSET MANAGEMENT

WHITE PAPER ///

Soiling: The Science & Solutions

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Nomenclature and Acronyms

AEP	Annual Energy Production
AR	Anti-reflection
AS	Anti-soiling
CAPEX	Capital Expenditure
Hz	Hertz
IRR	Internal Rate Of Return
Isc	Short-circuit Current
MWh	Megawatt Hours
OSM	Optimal Soiling Measurement
Pmax	Maximum Power Output
PM	Particulate Matter
PPA	Power Purchase Agreement
ROI	Return On Investment
SLI	Soiling Loss Index
SR	Soiling Ratio

Executive Summary

Many elements determine the optimum output of a PV module, one of which is the concept of soiling. Soiling occurs as a result of dirt, dust and other particles covering the surface of the PV modules. Dust composition widely varies across the globe, which affects both the type and amount of soiling. There are a number of methods to quantify and monitor soiling. These include conventional pairing of PV reference cells, as well as smarter methods, such as advanced data analysis. It is imperative to measure soiling for operational PV plants as well as pre-construction site surveys, since soiling can anticipate future performance. To eliminate the effects of soiling, panels require cleaning, which can be carried out utilizing either wet or dry solutions. The cleaning methods fall into the three main categories of manual, mechanised-manual and robotic cleaning (subdivided into automated or semi-automated). Although soiling cannot be prevented, its negative effects can be mitigated by means of deploying dust-repellent agents and coatings.

1. Introduction to White Paper

> **Soiling rates and soiling losses are often non-uniform across regions and climatic zones, and at times not even the same in one particular PV power plant.** –Greg P. Smestad, Ph.D

Solar PV modules have been paving the path for meeting the growing global energy demands in a sustainable manner and are expected to continue to do so. Nonetheless, photovoltaic modules require proper maintenance in order to generate their most optimum yield, which is heavily dependent on the amount of incident radiation reaching the surface of these modules. One factor hindering the performance of solar PV modules is the accumulation of dust particles on the solar cells, also known as soiling. The dust particles deposited on the PV cells decrease the transmittance of incident rays of sunshine to the cells, resulting in major output power degradation. Dust is generally defined as a Particulate Matter (PM), less than 500 µm in diameter. It originates from a variety of sources, such as wind, pollutants, airborne liquid constituents, particulates from construction and pollen. There is a wide dust variation around the globe in terms of colour and mineral composition. The dust composition affects both the amount and type of soiling or cementation. The dust properties and its deposition rates are also affected by ambient conditions, including humidity gradients, wind velocity and direction and seasonal variations. All in all, optimal dusty conditions tend to be- ironically- aligned with optimal solar conditions.

Another factor contributing to soiling is the concept of adhesion mechanisms affected by surface texture and energy of the module, tilt angle, humidity/moisture and re-suspension. Precipitation can also potentially further complicate the soil accumulation process by creating excess suspended soiling and alter the patterning of the soil. In order to fully assess the impact on the PV panel, the solar input needs to be considered as well. Potential hotspots rising from partial shading of the cells is another component influencing the soiling process. The soiling rate depends on a number of factors, including temperature and precipitation. Evidently, regions with a high soiling rate require regular cleaning, whereas areas with moderate soiling need less frequent cleaning and often solely during the dry season. Moreover, special circumstances, such as bird dropping and pollution, should affect the frequency of cleaning. The negative effects of soiling can be mitigated by continuous monitoring and measuring the amount of soiling, as well optimum cleaning schedules and methods.

Having a clear understanding of factors affecting soiling and its financial impact - i.e. on internal rate of return (IRR) of solar assets - is imperative when choosing the right strategy to overcome soiling. Furthermore, it is important to highlight that one strategy may not be applicable across the entirety of one plant, particularly in larger solar facilities. Thus, it is crucial to assess whether soiling is uniform across the plant, necessitating multiple deployment of monitoring solutions.

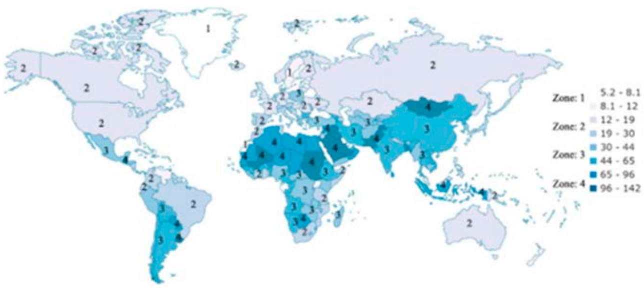

Figure 1: Dust intensity around the world

2. Main Factors Affecting Soiling

PM concentration is measured through soiling stations. For many years, the size of the particles has already been measured at weather stations around the globe for health and environmental purposes. Therefore, this data is usually readily available, but tends to be generated by stations distant from the PV plant. Thus, studies are now underway with the aim of correlating the relevance of that data versus the distance of the test site for PM from the solar plant. It is highly probable that in the future, just like measuring solar irradiance, PM sensors will be installed at PV sites. There are already companies selling these type of sensors. Nevertheless, these PM sensors remain in their infancy in terms of soiling, as this still is an emerging space within the solar industry. Asset managers can rely upon these sensors to measure particulate matter and that data can and will be used in PV plants.

Humidity and **dew point** are two other factors affecting soiling. These factors essentially influence cementation, defined as the process of dust particles sticking to the surface of the PV module and to one another. Cementation is particularly of significance in areas such as the Middle East and Central America. During cementation the chemical nature of particles themselves changes due to presence of water. These particles can become glued to the glass, making the removal process more difficult. The solar panel itself can cool down to a level at which dew forms and these droplets themselves contain aerosols and water. This impacts soiling through its stickiness and ability to form a more permanent bond to the surface. Dew formation is only beneficial if it is large enough, in which case it will actually help clean the panel. A study by Dr. Govindasamy Tamizhmani at Arizona State University indicated that a small amount of dew or rain does more harm than good, even in hot climates. There is a minimum amount of water required at a specific tilt, for a certain type of glass surface and a specific contact angle, to allow rain to clean the panels. Therefore, **frequency and amount of rain** also contribute to soiling, since they affect the natural cleaning of the panels.

Figure 2: Rain droplets on the surface of a PV module

3. Soiling Solutions

It is important to take into consideration the distinction between preventing soiling and monitoring as well measuring the amount of soiling, when discussing soiling solutions. Measuring soiling is of utmost importance for operational PV plants, as well as sites under pre-construction survey. In case of the latter, soiling measurements can anticipate future plant performance. In order to accurately assess the actual performance and optimize the washing schedule for a better return on investment (ROI), soiling ratio has to be measured in operating PV plants. Moreover, it is imperative to measure not only the short-circuit current (Isc), but also the actual maximum power output (Pmax) - particularly when using crystalline silicon modules - despite the need for more sophisticated equipment. This is due to the fact that small quantities of non-uniform soiling, which can potentially lead to substantial power losses, can not be detected solely through measurements of the short-circuit current.

One of the basic soiling measurement principles encompasses the pairing of PV reference devices with one clean and one 'soiled' point of reference. Selecting a PV reference device can be done based on the cell or the module, each of which has its unique advantages and disadvantages, depending on which pairing is used as the clean or soiled reference. The benefit of using a cell-to-cell method for soiling reference is that a cell is very compact and requires a low installation cost, However, it may soil differently in comparison with the actual modules, as factors like coatings, frames and size are not taken into consideration. On the other hand, using cell-module as the PV reference method is valuable, as it is best suited for automated washing and evidently accounts for the soiling on the actual module. One drawback is that it does require a greater amount of rack space when compared to cell-cell comparison. Module-module PV reference devices make for a simple and direct comparison concept, but require the largest amount of rack space and hinder automated washing. It is noteworthy to mention that soiling loss measurement varies depending on the time of day and thus it is recommended to consider the daily average. Furthermore, it is crucial to wash the clean reference routinely, given any chosen reference mix.

3.1 Measuring & Monitoring

Several solutions for soiling measurement are available on the market today. In this section we highlight a selection of these products.[1]

Ammonit Soiling Measurement Kit
The Ammonit soiling measurement kit helps determine soiling-induced PV performance losses by calculating the Soiling Loss Index (SLI), Soiling Ratio (SR), measuring of short circuit current, and the temperature of module surface. SLI can be measured directly from the solar PV module. It is defined as the loss in the irradiance that is received by the modules due to accumulation of dust, decreasing the transmission of the PV glass. The soiling loss index is calculated by comparing the irradiance of a clean control module and a soiled reference, the formula for which comprises a number of variables.

These include:

- Measured short circuit current of the module and the reference module
- Surface temperature of the module and the reference module
- Temperature coefficient of short circuit current

Alternatively, the soiling ratio is the measured ratio of soiled to control module outputs and is calculated using the effective irradiance that reaches the modules. The Ammonit soiling measurement kit takes into consideration the type - as well as amount - of precipitation and environmental factors, including pollution.

NRG's Soiling Measurement Kit

Another invaluable soiling solution is NRG's Soiling Measurement Kit, which supplies users with the information necessary to quantify the impacts of soiling, specific to the site. The data generated by this kit is intended to enhance the pre-construction annual energy production, also referred to as AEP, and panel washing schedules as well as the post-construction forecast models. The kit measures the temperature of, and short circuit current passing through, both the control and soiled module. This is based on the user's preference of statistical interval and optional 1 Hz sample, making for flexible analysis options in order to match data demands.

[1] *This selection was not based on commercial interests or compensation from the service providers.*

Figure 3: NRG soiling measurement kit

Campbell Scientific Soiling Index Measurement Solution

The CR-PVS1 Soiling Index RTU provides information that is required to assess and manage the effects of soiling on a solar PV plant. This solution is designed to be either the crux of an independant soiling measurement station, or serve as a supplement peripheral to a new or current MET station. The CR-PVS1 utilizes short circuit measurement methods and features:

- Real-time soiling loss index measurement
- On-board data filtering, ensuring quality data
- Daily calculation of average SLI

Dust IQ By Kipp & Zonen

Data accuracy is highly influential when calculating the soiling ratio, as low quality data results in a delay in the detection of losses, which can then lead to potentially major financial setbacks. According to measurement equipment manufacturer Kipp & Zonen, a difference in data accuracy between 3% and 2% can already result in a reduction of 20,000 euros per year for a PV plant with a production of 10 MWh. Therefore, in an effort to further increase the accuracy of soiling ratio, Kipp & Zonen launched a new unique technology, which aims to cover the missing link in the solar monitoring chain. This product is called 'DustIQ' and utilizes Optimal Soiling Measurement (OSM) Technology, which measures the sun reflection on a minute-by-minute basis. This data can then be translated into loss in power generated in real time. The DustIQ system is a relatively small device, weighs around 4kgs and is daisy-chainable, which enables the operators to connect multiple devices to form one string throughout the system.

Figure 4: Dust IQ

MaxSun Soiling Station by Nor-Cal Controls

MaxSun measures solar irradiance of clean and soiled references in watts per square meter by utilizing a single compact pyranometer. This station automatically calculates and records the percentage of soiling, as well as absolute soiling figure. Another key feature of MaxSun is its ability to allow on-demand measurements from remote systems. The recordings of measurements are stored in the onboard data logger with up to 50 days of storage capacity. MaxSun includes a unique and innovative mechanical door, which protects the reference module and decreases the need to frequently wash the control module.

Figure 5: MaxSun Soiling Station

AES PIT By Alternative Energy Solutions

Another method to measure soiling is to make use of an advanced data analysis platform, an example of which is 'AES PIT', developed by Alternative Energy Solutions. AES PIT is essentially an algorithmic toolbox for iterative machine learning. These algorithms are formed based on actual field data and account for environmental factors. However, the numeric output as well as the algorithms themselves are mathematically adjusted to avert any potential pitfalls they may be subject to. Monitoring by means of advanced data analysis can be best differentiated as having a movie of the plant versus a picture of it, which is merely a momentary snapshot and is very limited in terms of the information it provides. In addition, the soiling amount can be isolated for every unit through data mining, which can be used to generate a cost-benefit analysis to determine whether it would be necessary to clean the panels or not.

3.2 Preventive & Surface Modification

Soiling is a natural occurrence, which cannot be intrinsically prevented. Nevertheless, it is certainly possible to mitigate its negative effects by means of incorporating dust-repellent agents. Most PV cells are equipped with anti-reflection coatings (AR coatings). However, more and more companies are striving to develop anti-soiling coatings (AS coatings) in order to either prevent soiling from occurring or mitigating the risks associated with it. Module glass, which is treated with anti-soiling coating, is expected to not only soil at a slower pace but also to be easier to clean. That way, the modules maintain their optimal performance levels for a longer period of time. These coatings are also intended to reduce the costs per kWh of solar electricity produced in dust rich regions.

DSM AS Coating

A widely-known example is the anti-soiling coating produced by DSM, which is a Dutch company specialized in the science of materials. DSM has developed an innovative coating for glass PV solar modules with both anti-soiling and anti-reflection properties. DSM's coating claims to assist in optimizing the maximum power generated by the modules. Coupling glass solar modules with the DSM coating optimizes the cleaning process and decreases the soiling rate of these modules. Not only does this enhance the module performance, but it also lowers the number of cleaning cycles, as well as the resources required to carry out the cleaning of the solar panels. This coating accounted for less than 0.1% transmission loss in comparison with their AR coated solution or uncoated glass. DSM conducted a series of tests on panels coated with DSM AR coatings or their AS coating at a TÜV SÜD test site, located in Dunhang, China. The results indicated a better performance by the anti-soiling coating, by approximately 1.1% on a monthly basis.

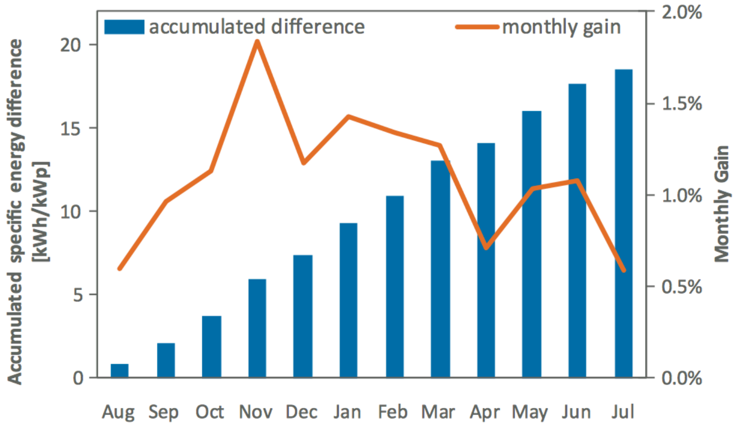

Figure 6: Accumulated specific energy difference (kWh/ kWp) at the TÜV SÜD site.

MoreSun Multi-Function Coating By CSD Nano

According to CSD Nano, the MoreSun Multi-Function Coating offers a unique pairing of AR and AS properties for the current solar photovoltaic modules. Due to the abrupt shift in refractive index caused by the mismatch of impedance, the rays of sunshine are partially reflected when entering a different medium, i.e. solar PV module. The MoreSun coating creates a barrier through forming crystalline pillars, facilitating the maximum light capture by the solar PV modules. Furthermore, PV panels that are coated with MoreSun have shown to be far less soiled, sometimes by as much as 80%, according to CSD Nano. The reduction in amount of soiling results in lower needs for frequent washing, thereby increasing the generation capacity of the module.

In addition to the aforementioned commercial coatings, current experimental research is devising another innovative dust mitigation technology. This method utilizes an **electrodynamic dust shield (EDS)** to lift and transport the accumulated dust off the PV panel via electrodynamic waves, which are generated by electrodes on the panel surface. This method is based on a non-contact mechanism, which minimizes the impact of mechanical damages, scratches and marks.

4. Cleaning Strategies & Solutions

As not all solar plants require the same frequencies of washing (or none at all), the million dollar question arises: To wash or not to wash? And if yes; how often to wash? In order to provide adequate answers to these questions, there are a number of factors to consider on each side of the scale. Evidently, washing is costly, which tips the balance towards the “Don’t wash!” side. Another major factor is the probability of Mother Nature providing a cost-free solution, thus taking impending rain as a factor. Furthermore, plant clipping and curtailment are two other factors that are discouraging the operators from washing, as the gains might not be that significant at times and the decision not economically sound. Nonetheless, there are valid reasons to opt for washing in lieu of leaving the panels as they are. Chief among them is the increased energy output. In addition, the PPA rates play an imperative role. The higher the selling price of the energy is, the more lucrative the washing becomes. In that sense, high (calculated) soiling creates the opportunity to generate additional revenue.

Another component of the aforementioned predicament in the solar industry is the question of how often to wash the panels. This question has been proven to be more complex to answer. Operators tend to follow a low-risk policy of washing once per year, right before the summer time, which is also referred to as the “money maker” months. David Young, former vice president asset management at Solarrus, has devised a mathematical formula to identify the ideal washing frequency. The formula is stated as: T=2W/r with the following variables:

- W: The cost of washing in US dollars
- T: The time between washes in days
- r: The rate of revenue loss due to soiling in dollars per day

Another upcoming cutting-edge tool in the soiling space is the AI-powered DeepSolar by Raycatch. DeepSolar operates remotely by conducting existing plant data analysis – with no O&M interference or hardware installation. In order to identify the optimum cleaning time of soiled solar PV modules and recommend the next cleaning date, DeepSolar considers the following elements:

- Overall accumulated loss due to soiling so far
- Predicted production in the near future
- Cost of cleaning
- Tariff of the produced energy

According to a case study conducted by Raycatch involving two solar plants of 4 MW capacity, population levels and land type were two main variables affecting soiling levels. Plant A was located in a populated area in the desert. Plant B was located in a non-populated area in the desert mountains. The two plants were located 30 km from one another. The daily soiling degradation level in the area varies from 1.2% to 0.25%. Regarding ratio of soiling, the case study discovered that the min-to-max soiling ratio in populated desert area (Plant A), during the same time periods, was 1:10. The analysis of Plant B (non-populated and desert-mountain) revealed that the ratio between different time periods, in exact same locations, can reach 1:10. As Plant A’s minimum was the maximum of Plant B’s, the overall Plant A/Plant B soiling ratio went up to 1:100

Overall, the dust has yet to settle on identifying the most optimal method to calculate the cleaning frequency of dirty solar modules.

4.1 Cleaning methods

4.1.1 Manual

Manual cleaning requires a human operator, with the assistance of mop, wipers or a vacuum suction cleaner. Therefore, in case of low labour costs, infrequent cleaning needs and/or a large available labour pool, manual cleaning is considered to remain the optimum method. However, when the inflation rate is high and there are concerns regarding sensitivity to module damage, this may not the most ideal cleaning method to use. Furthermore, this method is moderately dependent on plant design. The available system designs are flexible, ranging from wet or dry, which include dust broom, brush trolley and manual water brushes. Manual cleaning is utilized worldwide.

Figure 7: Mechanised-manual cleaning vehicle

4.1.2 Mechanised-manual

This is another cleaning method, which is most appropriate when washing is required on low to medium frequency (1-4 times a year). This cleaning strategy is mostly associated with high capital expenditure, but lower labour costs. This method is used primarily in the United States and tends to utilize water and tractor-based solutions., which still require human operation.

4.1.3 Robotic (automated or semi-automated)

This method is particularly beneficial for sites with high soiling rates, insufficient water supplies and/or high labour costs, as well as sites that are particularly large in size. However, in terms of sensitivity to upfront costs and tracker products, full-auto robotics are considered to be an inefficient cleaning method. A few examples of automated robots are rail-mounted, frame-mounted and free-moving-across-surface robots, as well as sprinkler installations., The latter two are typically used solely for rooftops. All in all, robotic cleaning strategies involve substantial CAPEX investments and are best suited for frequent washing schedules, such as those that require washing on a weekly basis. These method are highly dependent on the design of the plant and are mostly deployed in the Middle East and North Africa.

Figure 8: Addressable solar markets for autonomous cleaning (Source: GTM Research)

4.1.4 Water-free Robotic cleaning

Drought-stricken areas tend to account for both higher soiling rates and a greater number of solar installations. In addition, dry/water-free automated cleaning solutions increase the efficiency as well as production of solar systems. Thus, it would be highly valuable to leverage the existing waterless cleaning systems.

Figure 9: Ecoppia E4 Water-free automated cleaner

4.2 Overview of Commercial Mechanised & Robotic PV Cleaner Devices

Table 1 showcases an overview of some of the existing cleaning solutions, which are either fully commercial or in the early stages of commercialization.[2]

[2]This selection was not based on commercial interests or compensation from the service providers.

Device	Key target market	Type of brush	Pros	Cons
NOMADD (KSA)	Desert utility	Dry	• Fully Automated • Waterless • Fast	• Requires rails • Heavy • One device required per row
Greenbotics/ SunPower (USA)	Utility	Wet	• No additional rails required	• Requires water • Specific only to SunPower systems • Single module row width
First Solar/ DEWA (UAE)	Desert utility	Dry	• Waterless • Simple • Robust	• Labour costs • Imperfect results
Washpanel (Italy)	Temperate utility & roof	Wet	• No guide rails needed • Suitable for very wide rows • Dry cleaning possible	• Designed primarily for European climate • One device needed per row
SunBrush (Germany)	Temperate roof	Wet	• Suitable for wide rows • Simple	• Designed primarily for rainy climates • Guide rails needed • One device needed per row
Eccopia (Israel)	Desert utility, wide rows	Dry	• Waterless • Designed primarily for desert • Fully automated	• High degree of complexity • Guide rails needed • One device required for each row
Serbot Gekko (Switzerland)	Temperate roof, utility	Wet	• Fast • Suitable for utility-scale	• Heavy • Operator & support-vehicle required • Water-based • Designed primarily for European climate

Table 1: Overview of Commercial Mechanised & Robotic PV Cleaner Devices

5. Conclusion

Soiled solar PV modules have always been, and will remain, a cause of concern for solar asset owners and by now, most operators have come to realize that this issue will not simply blow over. Transmission losses due to dusty panels can vary significantly and are dependent upon climate conditions, localized terrain, tilt angle, the type of panels, and many other factors. Soiling remains one of the hottest areas of research within the solar industry. The demand for smart methods to measure and monitor this natural phenomenon will continue to grow in lockstep with innovative approaches to prevent it, as well as the increasingly inventive methods to clean the soiling, which cannot be prevented.

To learn more about soiling as well as other fundamental and cutting-edge topics related to managing, operating and maintaining solar assets, join one of our upcoming Solar Asset Management events. This line of unique conference is specifically dedicated to optimization of the operational phase of solar assets.

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Solar Asset Management Europe
(6th edition)
Milan, Italy
23-24 October 2018

Solar Asset Management North America
(6th edition)
San Francisco, USA
26-27 March 2019

6. Sources & Further Reading

A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches.

Ammonit Soiling Measurement Kit

NRG's Soiling Measurement

Soiling-Loss Index Measurement Solution

Nor-Cal Controls' MaxSun Soiling Station

DSM anti-soiling coating

*Measuring Soiling Losses in PV Arrays

Simulation of microscale particle interactions for optimization of an electrodynamic dust shield to clean desert dust from solar panels

QUANTIFYING SOLAR O&M'S DIRTY SIDE

Comparing PV power plant soiling measurements extracted from PV module irradiance and power measurements

Do You Wash Your Solar Modules Often Enough?

*Mechanical PV Cleaners

Power loss due to soiling on solar panel: A review

* Contact David Miller (david.miller@nrel.gov) for PBWorks access

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