PV Module Cleaning

Market Overview and Basics

In recent years, there has been increasing deployment of PV installations in desert regions. In these areas, regular dry-cleaning of PV modules is conducted to avoid potentially high-performance losses due to significant soiling. In this paper, an overview of typical PV module cleaning methods and systems used today is given. The cleaning systems are sorted into four main categories: truck mounted, semi-automated, portable and fully-automated. The potential impact of the cleaning methods on the PV modules themselves is also described and the technical requirements and specifications of each cleaning system are provided. Considerations for the selection of a specific method are evaluated and it is explained how to weigh the advantages of each system against capital and operational costs.

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Power loss through soiling

In recent years, an increase in PV systems installed close to the equator line has occurred due to the higher irradiation afforded at these locations. As these regions are often characterized by an arid climate, sand and dust deposited on the PV modules can significantly reduce the energy yield.

Closer to the equator, the soiling effect becomes more decisive because of the lower tilt angle of the installed PV modules. The typical equatorial setup is more designed to optimize performance for the higher incident angle of sunlight than it is to manage soiling. Therefore, in desert regions near the equator, several cleaning methods are often used to prevent performance loss.

Soiling (dirt, dust or sand accumulation) on the front side of PV modules is dependent on many factors and few general statements regarding soiling patterns can be made. The specific location of the PV system determines the prevailing soiling-type and climate. The main influencing factors are described in more detail in sections below.

Figure 1: PV modules in a power plant in a desert region with the top row soiled and the bottom row cleaned

Focus on dry cleaning

There are many different types of cleaning systems available on the market, each with its own advantages and disadvantages. In dry subtropical regions, PV module cleaning using water is rarely the optimal solution. In many cases, access to water is severely limited and can only be procured at high cost depending on the location. In some cases water may be easily available, but in the long run the use of water for cleaning puts too much strain on groundwater supplies. Local authorities may also prohibit the use of water for cleaning altogether. Considering that cleaning is mostly used in desert regions, cleaning with water covers only a small portion of systems deployed. Therefore this paper only deals with systems that use dry cleaning methods. Nevertheless, some systems have an option that allows cleaning with water at least occasionally.

Potential impact of cleaning on PV modules

In general dry cleaning is less effective than wet cleaning. The first reason is that water or other chemicals involved in wet cleaning serve as a medium through which dust layers containing salt or similar chemical deposits can be dissolved. The fluid also serves as a medium through which these particles can be transported away from the PV module surface.

For dry cleaning, dried layers of dusty materials are released through friction, and air is then the only medium through which particles can be transported away from the PV module surface. Both of these factors increase the difficulty of cleaning effectively without water or another fluid.

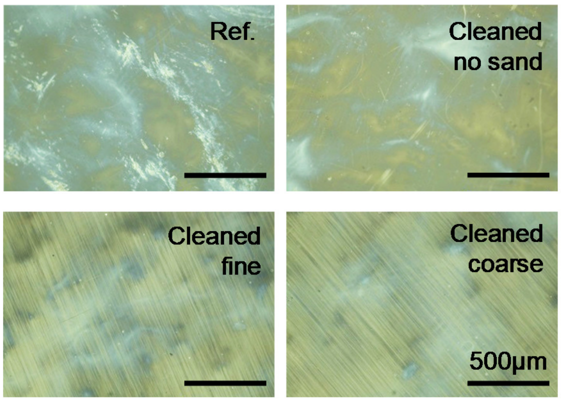

Figure 2: Light microscopy at x200 magnification after 1000 cleaning cycles on a reference glass surface and on glass surfaces exposed to cleaning without sand and cleaned with fine and coarse sand. [9] Image by Fraunhofer CSP.

The second concern with dry cleaning is that it may damage the PV modules due to the friction necessary to overcome the adhesion of the particles on the glass surface. Even when the brushing materials are soft, the dust particles themselves may scratch the surface. Additionally, in the case of 'sticky' dust, and if the cleaning frequency is not high enough, harder brushes may be required to remove the particles. Harder brushes must be tested for their abrasion impact on the PV modules.

PV module glass with an anti-reflective coating (ARC) is used by most PV module manufacturers in order to reduce reflection loss from the glass surface by up to 4 % [1]. Yield losses may occur due to ARC abrasion or surface scratches which decrease the anti-reflective properties of the glass surface treatment.

Some cleaning devices use the module frame as the 'carrying' point for the cleaning system. In such cases, it must be determined whether the PV modules can take the additional load without being damaged. Also, the cleaning load or pressure that acts directly on the front of the modules should not exceed the mechanical load carrying capability of the module. For modules with crystalline cells, a heavy or non-uniform load can lead to cell breakage or micro-cracking which in turn can lead to hot spots or power loss. Semi-automated systems have a particular risk of causing this type of damage because they have to be placed manually on every table of PV modules. The weight of these systems is generally between 35 and 65 kg.

In addition, cleaning during the day needs to be carefully carried out because there is a potential risk of harming the PV modules due to hot-spot generation as a result of partial shading. The hot-spot effect occurs when individual solar cells within the series circuit in the PV module are covered and shaded. This effect can be particularly critical in case of thin film modules without bypass diodes, as since single cells can be covered by the movement of the brush. To be on the safe side, the cleaning of the modules should happen at night in these situations. [2]

PV module soiling

Climate zones and power reduction

Depending on the latitude of the PV system, PV modules are installed at different tilt angles in different climate zones resulting in different soiling patterns as well as differing abilities of the PV modules to self-clean. With decreasing latitude and lower tilt angles, sand and dust play a more significant role in soiling.

In moderate temperature zones, module cleaning plays a less important role (except in the case of anthropogenic soiling as described below). In these climates, tilt angles above 12° and precipitation throughout the year leads to a good self-cleaning of the PV module surfaces. In Germany, for example, soiling-related performance losses are usually only around 1 % without cleaning [3]. Disadvantages of this climatic zone are the good conditions which exist for plant growth such as mosses and lichens, which can occur after a certain period of time (months to years).

Figure 3: Power plant in Israel, with soiling losses measured > 20 % [15]

With increasing proximity to the equator, semi-arid and arid regions becomes more common. Less precipitation results in a less of self-cleaning effect. Furthermore hot temperatures, less vegetation and higher winds lead to sand and dust becoming the main soiling concern. These regions suffer from a high concentration of atmospheric dust as well as sand storms [4].

Figure 3 shows an example how dust accumulates on PV modules.

In desert regions, daily performance losses ranging from 0.3 % up to 1 % have been measured [3]. Moreover inhomogeneous dirt distribution may lead to hot-spot generation [2]. If the soiling contains salt it may also help drive Potential Induced Degradation (PID) of the PV modules [5].

In Figure 4 a dust event is shown to visualize the impact of dust in arid regions. Major sand storms are generally not regularly distributed over the year [3].

Figure 4: Example of dust storms, Israel Timna-Park

With tracking systems, soiling can be reduced during sand storms and at night by placing the modules at their maximum tilt angle in order to minimize dust accumulation. In any case, the variable tilt angle of trackers increases the natural cleaning due to gravitational forces. Tracking systems have been proven to have smaller angular losses due to soiling in comparison to fixed modules [6].

Due to the lack of precipitation in arid areas, the sand or dust can fairly easily be wiped off the modules. In contrast, in regions with some level of humidity or salinity in the air [3], dew may lead to a cementation of the sand or dust on the surface (see Figure 5) [4]. Cemented particles require more effort to clean the surface.

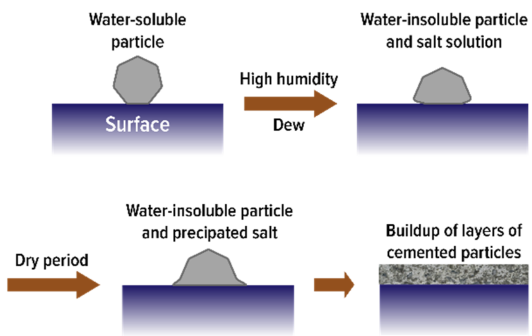

Figure 5: Cementation effect due to dirt (simplified) [10].

Soiling particle types

The exact system location plays a major role in the prevailing sand and dust type, their properties, and consequently their ability to be easily removed.

Studies have shown that fine sand particles are more challenging than coarse sand particles. First of all, fine sand has a much higher shading impact on the PV modules compared with the same amount of coarse sand [7], causing higher power losses. The second major impact is on self-cleaning. Coarse sand particles can be more easily blown off by the wind compared to fine sand [3, 4]. This also applies to module cleaning solutions that use high-pressure water without any manual scrubbing. Small particles can remain stuck to the module [8].

On the other hand, sand with large grain sizes and a variety of different particle shapes have an increased abrasive effect on the module's anti-reflective coating (ARC) layer and glass surface during cleaning and sand storms [9]. For proper laboratory testing of cleaning systems, the specific type of sand expected at the system location must be used. (Figure 6)

Figure 6: Sample sand from the region of the Rub'al Khali desert

Soiling due to anthropogenic pollution

In addition to soiling induced by natural events and climate conditions, anthropogenic pollution needs to be considered. It is an important root cause of power output reduction for PV systems in the vicinity of, or in, cities with high traffic or coal-fired generation plants (or comparable heavy industries). Systems in these locations can suffer from soiling due to industrial soot particles [11, 12, 13]. This type of dirt is very 'sticky' and requires a higher cleaning effort. Quarries, cement factories [14] or dusty roads close to, or within, the PV system can lead to rapid and inhomogeneous soiling within a short period of time. PV systems in the vicinity of, or on, the rooftops of livestock farming buildings can also be exposed to soiling due to dust and airborne organic fibers.

Overview of cleaning methods

Four types of dry cleaning can be technically distinguished from each other: ***truck-mounted***, ***semi-automated, portable*** and ***fully-automated***. All of these are described below.

Truck mounted

Truck-mounted cleaning systems consist of a brush attached to a truck or other vehicle, which drives between the PV module rows. Normally, the brush is located on a crane jib, which places it over the PV module. Each machine has its own system for controlling the pressure of the brushes on the PV modules in order to avoid any PV module damage.

With this type of cleaning system distance and tilt angle deviations between module-mounting structures do not constitute a problem. In order for the vehicles to reach the PV modules however, a minimum distance is required between the rows. This depends on the device and ranges from 2.5 to 3 meters. In addition, a maneuvering area at the end of the rows is necessary so that the vehicle can easily turn around.

The weight of the cleaning device on top of the PV module must be within the tolerances allowed by the module manufacturer. Truck-mounted devices are associated with a higher risk of PV module damage because irregular ground conditions may cause the brushes to exert a higher pressure on the PV modules with consequent cell or PV module breakage.

Truck-mounted cleaning requires at least one worker, who must be specially trained. The training is usually provided by the equipment manufacturer. The worker sits in a vehicle, which usually has air conditioning. Since most vehicles are equipped with spotlights, the system can also be used at night.

Examples of companies which provide a truck mounted cleaning device are BP Metalmeccanica and SunBrush mobil GmbH.

Figure 7: BP Metalmeccanica telescopic cleaning device [BP Metalmeccanica S.r.l]

Semi-automated

Semi-automated cleaning devices must be placed at the beginning of each PV module-mounting table. The device then moves automatically in one direction over the surface of the PV modules. After completing one PV module table the device has to be carried and placed onto the next PV module table by hand. The machines have generally a sensor for detecting the end of the row so that they return automatically. In most cases they move using the module frame, in other cases, they move directly using the PV module surface for traction.

The integration of these devices can be done after construction of the PV system without much difficulty. Requirements for this type of cleaning solution to be used are PV systems with long arrays and no gaps or relative tilt angles between PV modules. Long arrays reduce the number of cleaning devices required. Gaps, relative tilt angles and steps between PV modules can be difficult to overcome with this device. Each device has its own limitations in overcoming these factors. The device should also smoothly move across the array for the lifetime of the array. All semi-automated products operate with an on board battery.

An advantage of semi-automated systems is that, when they are not needed, they can be stored in protected environments, which may increase their life time.

Most semi-automatic systems require two workers to move the devices from one table row to another. The cleaning itself happens automatically.

There are several companies which provide a semi-automated cleaning devices. Examples are Energy Guru, G.S.I ltd. (Geva Solar Innovations), Miraikikai Inc., Washpanel s.r.l., and PV Hardware.

Figure 8: Geva-Bot from G.S.I. during module cleaning [G.S.I.]

Fully-automated

Fully-automated cleaning devices are installed on each row of a PV system and are stored at a parking station at one side of each row. They are programmed to move along a single module row only. Most of the devices have an error detection system and take weather conditions in consideration before they operate. All fully-automated products operate with an on board battery, although some devices may be additionally charged by their own PV modules.

Figure 9: Fully automated cleaning system by Ecoppia [Ecoppia]

Fully automated devices may have an additional rail system installed; obstructions between tables (space, steps and tilt) have to be taken into account. The Ecoppia device requires a minimum tilt angle of 17° as it moves from top to bottom driven by gravity. The Kashgar Sol-bright photovoltaic Technology can be installed on single axis tracking system. The

Nomadd Desert Solar Solution can operate in either semi- or fully-automated mode.

As the name implies, fully automated devices do not require any manual labour for the cleaning process or for the positioning of the devices. Fully-automated devices can also operate during the night.

Figure 10: The Kashgar Sol-bright Photovoltaic Technology can be installed on not only on fixed mounting systems but also single axis trackers [Kashgar Sol-bright]

Portable robots

Portable robots are devices up to one square meter in size which move on the surface of PV modules. When operating autonomously, like the Mirikai robot or Raybot from Ecovacs Robotics, they have sensors and a control system for detecting the end of the PV module surface and change direction in order to clean another part of the module array. Other devices, like the Gekko Solar or Innovpower robot, are driven by remote control. In this case manual inputs are required.

Some robots have limitations with respect to the tilt angle (maximum of 15° for the Mirikai device for example). Others like the Raybot device from Ecovacs Robotic or the Gekko device, adhere to the PV module surface using a vacuum which allows cleaning of modules with a higher tilt angle (up to 75° for the Raybot device).

Due to their configuration, portable robots are the most used solution for rooftop installations and trackers.

Future technologies

Some new technologies for dry cleaning of PV modules have come to the market in recent years.

Drone cleaning system

The 'SolarBrush' drone recently developed by Aerial Power (Germany/UK) is equipped with a brush that sweeps dry dust and dirt from the surface of the PV modules. This contrasts with the mechanized options of other cleaning devices, which run the risk of damaging surfaces by applying forces from wheels and suction cups.

It is easy to transport and requires few staff. The system cleans an entire solar PV system, using pre-programmed flight paths. Up to eight different drones can be distributed over the PV system by a single person. The drone can move along a PV module row with an angle up to 35°.

High voltage based cleaning system

The TAFT robots from Taft Instruments use a high AC voltage electric field to move dust and dirt away from the PV modules. The robot clamps to the edges of the module using motor driven rollers like a semi-automated system. Electronics inside the device generate a high AC voltage that is applied to conductors close to the PV module surface. The charged particles oscillate along the field line. As the robot moves over the PV module, dust is pushed towards the edges where it eventually falls off. The robot uses infrared through optical beam sensors to detect the limits of motion. It requires no maintenance or external power. PV cells supply the power for the robot. As it does not require significant energy storage, it runs only when the sun shines. This cleaning method may damage PV modules, particularly in the case of thin film modules without bypass diodes where single cells could be shaded and hot spots generated. The inverters should be switched off during cleaning to avoid module damage.

A prototype ultrasonic cleaning system has been developed. The device removes dust from the PV modules by creating a vacuum cavity within the medium (air or/and water) during the rarefaction cycle [16]. No devices using this technology are on the market yet.

Technical requirements

The following section lists some of the high-level technical requirements for dry cleaning systems.

General

- The specific soiling present at the site needs to be well understood and characterized.
- The weight of the cleaning device on top of the PV module must be within the allowable loads given by the PV module manufacturer.
- The module manufacturer should provide explicit approval for each cleaning system to be deployed, including confirmation that warranty coverage of the module will not be voided by use of the system.

Modules

- Minimal abrasion of the PV module anti-reflective coating and scratching of the glass surface should occur. To evaluate the abrasion risk, cleaning system suppliers should use an independent third party to test the devices.
- No cell or PV module breakage or damage should occur which could impair the safety, mechanical or electrical integrity of the PV modules.

Cleaning System

- The selected system should be technically robust for the respective operating environment. No sensitive parts should be exposed in desert conditions.
- Minimal maintenance of the cleaning device should be required. Ideally unskilled, low-cost labor can be used to perform maintenance on the cleaning devices. Maintenance should be easy, fast and require few tools.
- In the case of semi-automated, autonomous and fully-automated devices the number of hours required for battery charging and the battery lifetime should be considered. Remote battery status monitoring is preferred.

System Supplier

- The cleaning system supplier should provide operator training on the correct use of the system.
- Given that the economic and operational lifetime of many PV systems is expected to be at least 25 years, the cleaning system supplier also needs to guarantee the supply of spare parts for the same time period.

Investment costs

The price of cleaning systems is highly variable. The investment cost for truck mounted systems is usually between 120 k€ and 150 k€, including the truck. The semi-automated systems are relatively cost-effective with system prices from 2 k€ to 12 k€. Trucks and semi-automated systems may also be used to clean multiple systems as the cleaning devices can be driven from one system to the next. The price of a portable robot can be around 70 k€.

A fully automated system for a 10 MW power plant will cost around 450 k€. Considering the high investment costs, it has to be demonstrated that the device can reliably clean the PV modules every day at a very low operational cost.

There are additional costs for non-automated systems. Truck mounted systems need a driver and consume diesel fuel as operational expenses. The semi-automated systems require at least two workers to clean a PV system.

These additional operational costs are heavily dependent on the required cleaning frequencies. At low cleaning frequencies, the use of truck-mounted or semi-automated equipment is advantageous. For high cleaning frequencies, the advantage shifts towards fully-automated devices. Even though these systems have a higher capital cost, the systems usually incur lower operational cost, so the higher upfront investment becomes attractive.

Every PV system requires an individual analysis to determine the cleaning costs based on the type of cleaning system selected. If cleaning costs are taken into account at the PV system planning stage, and efforts made to minimize these costs, it can be assumed that all systems will incur lower O&M costs and deliver higher performance compared to systems where cleaning is not planned in advance. This particularly applies to fully automatic systems, due to the high potential for cost savings.

The cost of annual maintenance is the same for semi- and fully-automated devices. The maintenance of a truck-mounted device is clearly higher because of the truck itself and its regular maintenance requirements.

Choice of Cleaning Device

Cleaning requirements (frequency and cleaning method) are very much site dependent and need individual decisions for each PV system and its location. The following factors should be taken into consideration when choosing the most appropriate cleaning device:

Expected soiling levels

- An important factor are the expected climate condition(s) at the site, determined by a combination of rain, relative humidity, dew, wind and ambient temperatures over the course of a year.
- Another important factor is the type of soiling particles that will be predominant: shape, grain size and other elements that are included in the particles.
- In the case of anthropogenic pollution, busy roads, a big city or industrial sites can increase the level of soiling; agriculture and farming typically have an impact on the environment and soiling. Seasonal effects like pollination or seeding can also have a strong effect on soiling.

Frequency of cleaning

- An appropriate cleaning frequency should be determined by considering the soiling rate (with the consequent PV system yield reduction) and the costs of the cleaning process (including both capital and operational costs over the lifetime of the system).
- In PV systems where moderate soiling is present, or only seasonal soiling events are predominant, the first choice is usually a truck-mounted or semi-automated cleaning system. The more regular and dense the soiling, the more likely a fully-automated system is the most attractive solution.

Type of PV plant

- The design of PV systems can be highly variable. This has to be taken into account very carefully when choosing the appropriate cleaning system. The mounting arrangement of the PV modules plays an important role.
- Truck mounted systems require a minimum distance up to three meters between the module rows.
- The tilt angle means that some cleaning systems cannot be used. There are cleaning systems that require a minimum angle and systems that can only work safely up to a defined maximum angle. In the case of tracking systems, any tilt angle is theoretically possible. For trackers, portable devices are the most likely choice.
- The next consideration is the length or height of the mounting table, which determines the length of the cleaning brush required. Some cleaning systems only offer specific brush lengths.
- For every cleaning system, long module rows are beneficial to reduce the costs. Depending on the size, a gap between PV modules may cause an interruption in the cleaning process. This means that either the cleaning device needs to be manually transferred or, if it is permanently installed, a new device must be installed.

Proximity to labor sources

- Another decisive factor is whether the PV system is near a settlement with available low cost labor or in a remote region with no local low cost labor. The further away a PV system is from settlements, the higher the potential labor costs and the more advantageous a fully-automated system may be.

Type of module

- Some cleaning devices use the frame as a carrying point. It must be verified whether the modules can take the additional load, in particular in the case of frameless modules. Also, the load that acts directly on the front of the modules should not lead to mechanical damage or abrasion. Finally, the anti-reflective layer of the glass will likely see constant abrasion during regular cleaning. Depending on the type of anti-reflective layer used, the hardness of the brush may need to be adjusted to prevent unwanted transmission losses.
- The willingness of the PV module manufacturer to approve the use of specific cleaning systems and honor module warranties without additional restrictions or limitations is also an important consideration.

Qualification standards under development

There is currently no standard that regulates the qualification of cleaning devices. This means that every test procedure used to evaluate cleaning devices has to be checked carefully for its appropriateness and effectiveness.

Based on the information available today, the following institutes have carried out testing of cleaning devices: Quality Institute Srl, TÜV Süd, TÜV Nord and PI Berlin. PI Berlin has already tested several types of cleaning systems.

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 device operation in a specific PV system. This means that specific module types are tested in combination with a specific type of soiling, cleaning frequency and PV system design. It is therefore difficult to provide a general qualification for any particular cleaning system as the test can only be valid for the specific case which has been evaluated. A new PI Berlin standard test for cleaning devices is under development. The new test protocol will be designed to be independent of the specific PV system. It will give a general assessment of the quality of the device regardless of specific soiling conditions, module type and PV system design.

Conclusions

Cleaning requirements (cleaning approach and frequency) are very site and system dependent and require individual decisions for each PV system location. The most important influencing factors are:

- Climate: rain, relative humidity, dew, wind and temperature
- Soiling: amount and type, sand particle composition and size, the presence of anthropogenic or agricultural pollution
- PV system: configuration, layout, mounting structure, ground conditions and size

Four main groups of cleaning systems have been presented: truck-mounted, semi-automated, portable and fully- automated.

Truck-mounted and semi-automated devices are more suited to PV systems that are not subject to a high level of soiling and where a variable cleaning frequency is sufficient. In comparison to fully-automated devices, they require less capital investment but have higher operational costs.

Truck-mounted devices are associated with a higher risk of causing PV module damage where irregular ground conditions are present. In case of the semi-automated solutions, only the first PV modules in a row are potentially subject to damage.

Portable devices are used for rooftop installations and trackers. Fully-automated solutions are more suitable in situations with high soiling rates, when high cleaning frequencies are required (monthly to daily). Due to the higher capital investment, these systems are more typically applied in larger PV systems. Fully-automated devices typically have control and monitoring systems that allow cleaning schedules to be programmed depending on weather conditions and include an error detection and battery charge monitoring systems. Some equipment provider also offers a soiling monitoring system to determine the soiling rate and act accordingly.

The long-term availability of an individual cleaning system is very difficult to estimate because almost no system has been in field operation for more than five years and each system has had a different level of commercial exposure (from only prototypes up to GW-scale deployment).

The selection of the appropriate cleaning system for a particular PV system must be taken on a site by site basis together with a commercial evaluation by the PV system planner, owner and operator. A technical decision should be made based on the high-level technical requirements provided in this paper. Approval should always be sought from the PV module supplier to ensure that no loss in warranty coverage occurs and the suppliers' knowledge about the PV module can be taken into account.

About the Author

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