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CLEANING METHODS FOR DUST DEPOSITED ON THE FRONT COVER OF PHOTOVOLTAIC MODULE

Abstract: Photovoltaic modules are one of the renewable energy sources with great potential for application in various regions of the world as well as for different terrain. They are, however, sensitive to external factors, affecting the overall amount of energy generated, such as solar irradiance, shading effects and any form of soil build-up on the front glass cover of solar device. The latter issue happens over a course of weeks, months and years and the exact pace is determined for a specific location. Nevertheless, dust remaining on the module surface limits the amount of solar irradiation that can reach solar cells. It then leads to a lowered maximum power and correspond to a decrease in energy yield. A way to mitigate soiling effect, outside of natural washing dependent on precipitation, is a regular debris removal. The proposed methods utilise different approaches, namely active cleaning such as manual, mechanical or electrodynamic, or passive cleaning by applying additional hydrophobic or hydrophilic coating to slow down the accumulation tempo.

Keywords: photovoltaic modules, surface soil, power decrease, efficiency decrease

Introduction

Over the course of few decades there is a prevalent approach to cut back on fossil fuels' contribution in the overall energy balance. It resulted in dynamic development of Alternative Energy Sources (AES) sector, including photovoltaic (PV) industry. A few advantages of AES are their eco-friendly approach, reduction of carbon footprint, lower maintenance requirements and prosumer independence from the main power grid.

Considering photovoltaics, between year 1992 and 2021 there was an almost thousand-fold increase in cumulative installed capacity [1]. According to data provided by the International Energy Agency total cumulative capacity exceeded 760 GWp, while 140 GWp was installed in just one year 2020 [2]. Even higher annual average capacity addition reaching almost 300 GWp is expected for years 2021-2026 [3]. Overall, solar energy is responsible for nearly 60 % of all renewable capacity surplus worldwide [3]. Additionally, it was observed that PV industry is dependent on both production infrastructure and power grid development, and is a significant component in the growth of energy systems [4].

However, to fully benefit from PV installations a few factors have to be addressed. Maximum energy yield is highly dependent on module tilt angle and azimuth, temperature changes, solar irradiation fluctuations, front surface shading and soil accumulation [5].

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Soiling effect

Dust deposition comprises mainly ambient particulate matter (PM) settlement on the front cover of photovoltaic module and is a phenomena that is present in each location over a course of time [6]. It is often underestimated, but can lead to reduction in conversion efficiency, since the amount of light reaching solar cells is diminished due to contamination buildup [7]. Lower irradiance directly corresponds to lesser current values, which links to reduced power generation output. PM concentration has a nonuniform distribution and is closely linked to location, as exemplified in Figure 1 by World Health Organization (WHO). WHO takes into consideration only air suspended pollution of a diameter under 2.5 μm (PM2.5) and under 10 μm (PM10) [8]. It can be concluded that most developed countries face pollution, which is especially important since those nations invest in renewable energy and incorporate PV installations on a daily basis.

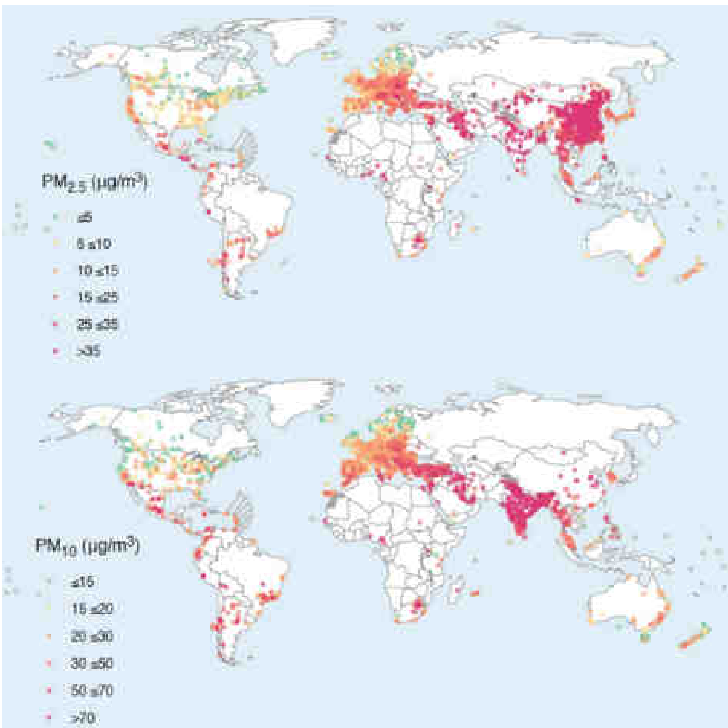

Fig. 1. Volume concentration of air suspended pollution with a diameter under: 2.5 μm, and 10 μm (on the basis of: [8])

To further illustrate how dust deposition depends on various factors, they were presented in Figure 2. Some aspects cannot be easily changed, such annual precipitation, humidity and wind, other may be slightly altered - for example tilt angle.

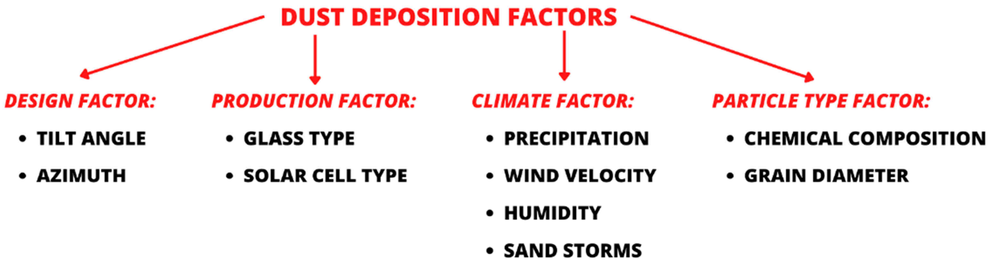

Fig. 2. Factors affecting soiling effect on photovoltaic modules

The rate of dust deposition depends heavily on the PV installation location, because it accounts for climate and particle type factors. As a result, regions in Middle East and other areas close to deserts are facing accumulation at an especially fast pace due to sandy environment. Power losses may reach even 70 % in just one hour, when a sand storm occurs [9]. Higher than average humidity and dew also act as a drawback, because it enables particle deposit to stick heavily to the surface [10].

Aside from environmental issues, soil agglomeration may differentiate based on site-specific pollution like products of exhaust emission, pollens, mud, tree leaves, bird droppings or - in seaside areas, accumulation of salts [11]. In this respect, solar power plants placed in regions characterised by heavy and frequent wind, as well as precipitation, benefit from it and experience partial capacity restoration.

Various cleaning methods can be proposed as a way to mitigate the effect of soiling, as shown in Figure 3. Natural cleaning constitutes mainly of rain and wind, however it usually leaves debris and is insufficient in the long run. Heavy soiling that occurs after a significant period of PV installation exposure to external elements should not rely solely on this method alone. Mechanical methods can be either automatic or using manpower and they incorporate cleaning with brushes or cloths. Combining manual approach with water rinsing is thought to bring the most efficient dust removal. This is, however, problematic in dry areas, where water is used sparsely. Other methods of soil removal are based on electro-dynamic screens (EDS) and self-cleaning coatings.

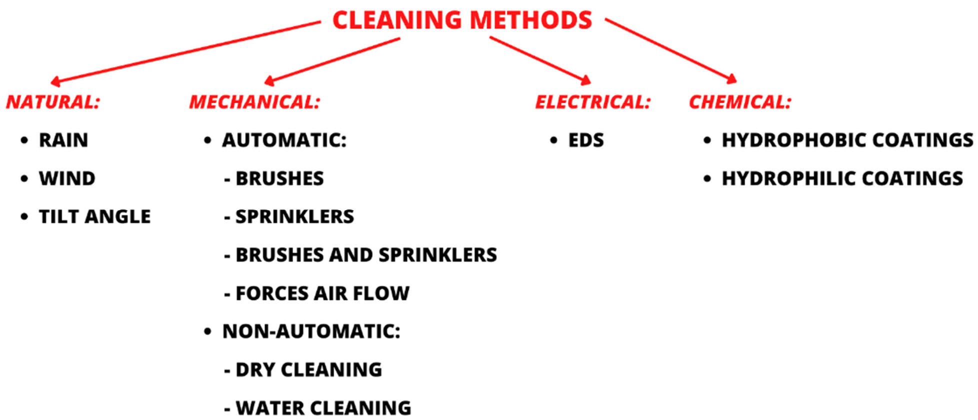

Fig. 3. Cleaning methods proposed for photovoltaic installations

A period between each complete PV installation cleaning, which restores its full capacity, is called cleaning cycle and can vary between different locations [12]. Jian et al. compared different previous studies carried out in desert areas and concluded that it is best to apply some type of cleaning method every three weeks [13]. Additionally, they noted correlation between dust particle diameter and the covered surface area. Smaller particles are responsible for denser distribution. They are also harder to remove from PV module surface. This leads to a finding that soil with bigger grains not only is less likely to stick to the surface because of gravity, but also can be cleaned at a faster rate.

Calculation of overall total cleaning cost is very specific for each solar installation, as it includes labour cost, water price, or any additional equipment that is specific for an applied method. It was stated that for larger PV installations, of several tens of MW, machine cleaning is superior to manual labour, since it cuts the expenses by 50 % [14].

Natural cleaning

This solution takes into consideration such aspects like environmental conditions, namely rain and wind, but also mentions the preventive outlook utilising gravity force. Independent research groups proved that soiling rate is lower for higher tilt angles [15-17]. Therefore, it may be beneficial to apply in regions, where expected energy yield does not decrease significantly with different tilt angle and so it can be adjusted accordingly. Notwithstanding, it should be noted that tilt angle approach does not prevent dust accumulation over time.

Wind is a leading cleaning form for arid climates with very little rainfall. Figure 4 visualises three removal mechanisms which were observed - direct lift-off, sliding or rolling [18]. They mainly depend on wind velocity, dust particle diameter and friction coefficient for surface-particle interface. Research carried out by Ilse at el. proved that removal by rolling is dominant process in soil detachment [18]. It is however possible only on rough, dry surfaces and for dust with grain size over 10 μm [18, 19]. Further course of soil accumulation enhances particle adhesion, thus rendering wind impact insignificant.

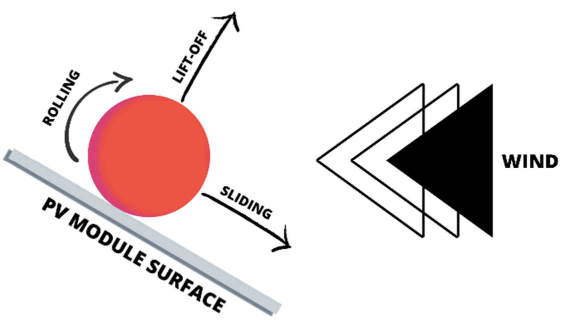

Fig. 4. Mechanism of dust removal by wind

Rain is an effective cleaning way for PV modules installed in regions with regular seasonal precipitation. Here two processes may be considered - accumulated soil dissolving from the surface and particle pickup by the water [20]. Threshold for daily rain amount to start this cleaning method varies and reported minimum values include 0.3 mm [21], 5 mm

[22] and even up to 20 mm [23]. Such a wide range in data could be explained by different components, including PV module inclination, PV module surface wettability, raindrop velocity, soil type and its adhesion state [18].

Mechanical cleaning

Mechanical cleaning first and foremost is divided in two groups - automatic (robotic devices, drones) and non-automatic (manual labour). In manual cleaning accumulated soil is removed with brushes with soft bristles or cloths, as they are more effective than natural precipitation. Shehri et al. suggested that foam brushes with silicon rubber as well as nylon cloths are the best choice of tools [24]. Pure water, preferably deionised, may be added to this cleaning process, as it does not form any residue [25]. It is advised against applying chemically active materials as cleaning agents to ensure module degradation is not impacted.

Automated mechanical cleaning helps to cut on the manual labour costs as well as program cleaning cycle so that it corresponds with region-specific environmental factors. It can be performed without water - with soft brusher, but also with water spraying systems, combining sprinklers and brushes or by applying forced air-flow. Some researchers recommend monthly or even weekly cleaning for dry climates with occurring sand storms [5, 26]. A study performed by Mazumder et al. demonstrated conversion efficiency increase by 15 % for a water spraying robotic system [27]. Another experiment, executed by Baloushi et al., included self-powered robot with microfiber brushes, air blower and microcontroller to enable autonomous work [28]. Laboratory tests are promising, as it was concluded that 99% of soil accumulated daily was removed. Jaradat et al. also built cleaning robot, which was equipped with brushes and was able to move horizontally and vertically on PV installation [29]. The laboratory results showed that 80 % of dust build-up was wiped off. Figure 5 further illustrates machine cleaning with sprinkler system and with autonomous robot.

a) b)

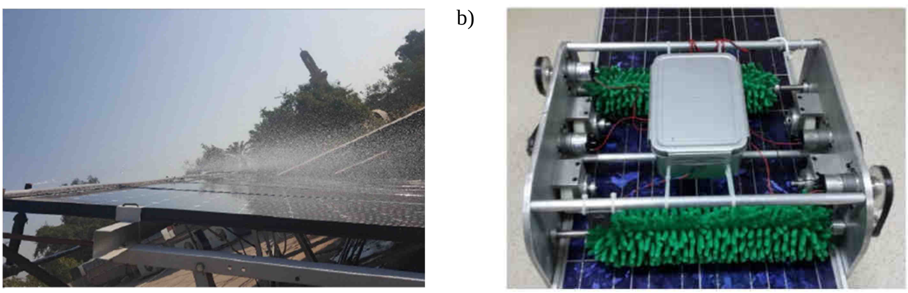

Fig. 5. Mechanical cleaning method: a) water sprinkler [30], b) autonomous robot [29]

There are many companies which specialise in non-automatic and automatic cleaning services as well as cleaning machinery sale. An overview of a few firms was presented in the Table 1 and Table 2 - for non-automatic and automatic systems, respectively. To provide further insight it should be stated that some companies, like SunBrush, presume their clients are aware of the need to mount the device on a vehicle, while other, like BP Metalmeccanica, sell their product as a whole machine with a telescopic arm.

Table 1

Companies offering non-automatic cleaning equipment dedicated for PV systems

Company	**Model name**	**Description**
SunBrush Mobil [31]	SunBrush Mobil Compact	Equipment: rotating long brush Brush arm: 180° swivel Cleaning: with or without water PV system tilt angle: the whole range
	SunBrush Mobil Rapid	
hyCLEANER [32]	hyCLEANER SOLAR facelift	Equipment: rotating brushes Cleaning: with or without water PV system tilt angle: 25°/47° (with accessories)
	hyCLEANER solarROBOT	
BP Metalmeccanica [33]	SOLAR CLEANER F3500/C4000 Telescopic	Equipment: rotating long brush Cleaning: with or without water
Kärcher Home & Garden [34]	iSolar 800/400	Equipment: rotating brushes Working range: up to 13.7 m Cleaning: with water

All of the non-automatic devices described in the table above were further illustrated in Figure 6.

a)

b)

c)

d)

e)

f)


Fig. 6. Mechanical cleaning method: a) SunBrush Mobil Compact [31], b) SunBrush Mobil Rapid [31], c) CLEANER SOLAR facelift [32], d) hyCLEANER solarROBOT [32], e) SOLAR CLEANER C4000 Telescopic [33], f) iSolar 800 [34]

Table 2

Companies offering automatic cleaning equipment dedicated for PV systems

Company	Model name	Description
Ecoppia [35]	Eccopia T4 Eccopia H4 Eccopia E4-E4+	Equipment: rotating brush Cleaning: without water PV installation: fix tilt angle or with solar tracker Energy dependency: own power supply
NOMADD [36]	NOMADD 1P Edge Runner NOMADD 2P Edge Runner	Equipment: rotating brush Cleaning: without water PV installation: fix tilt angle or with solar tracker Energy dependency: own power supply
SCM [37]	SCM S1	Equipment: rotating doubled brush Cleaning: with or without water PV installation: fix tilt angle Energy dependency: alternating or direct current
SunPure Technology [38]	SunPure	Equipment: rotating brush Cleaning: without water PV installation: fix tilt angle Energy dependency: own power supply

Automatic cleaning devices can work individually or be interconnected for bigger solar farms application. Some of them, like Ecoppia or NOMADD, are intended specifically for usage in arid climate, as they offer cleaning without water spraying. They also offer a variety of features including automatic angle adjustment for misaligned rails, detection of rail distance changes between arrays, dedicated monitoring and controlling system accessible online and offline as well as speed adjustment.

All of the automatic devices described in the table above were further illustrated in Figure 7.

a) b) c) d)

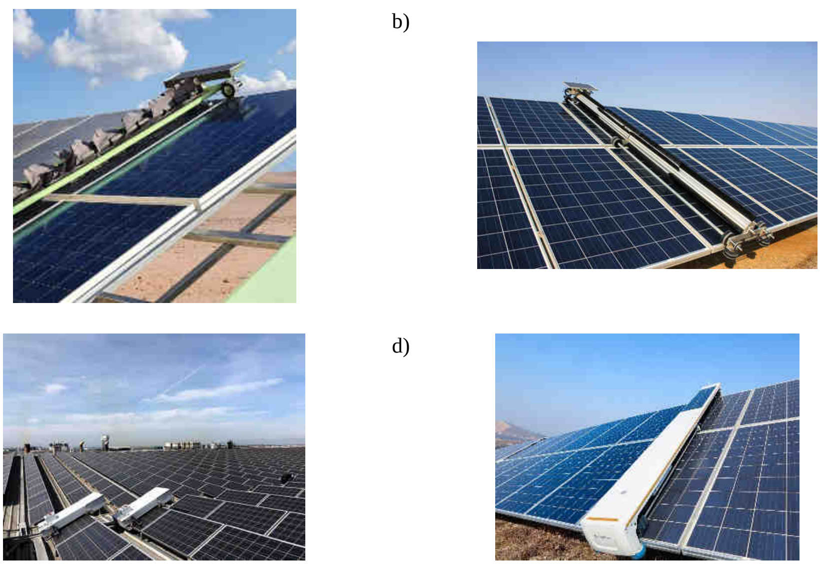

Fig. 7. Mechanical cleaning method: a) Ecoppia H4 [35], b) NOMADD 2P Edge Runner [36], c) SCM S1 [37], d) SunPure [38]

Electrical self-cleaning

This method utilises electric curtain concept and is still in a test phase and under constant development. Transparent electrodynamic screens (EDS) are created by a layer of electrodes placed on top of a front PV module surface, as seen in Figure 8 [39].

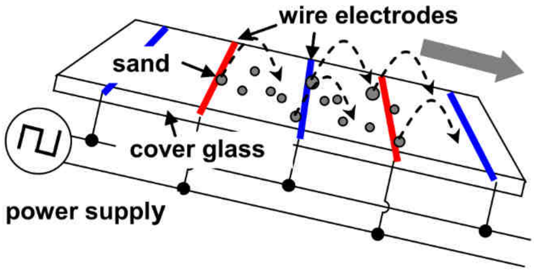

Fig. 8. Schematic overview of electrical dust removal mechanism [39]

In the first model a single-phase high-voltage was used to create an electric field on such area, which in turn allowed to move soil particles to the edge of solar panel. The second model operated on two-phase low-frequency high voltage [40]. EDS reported large efficiency value measured in laboratory conditions and results in 90 % dust removal within 2 minutes [41]. Efficiency for a commercial device is significantly lower, as it can reduce soiling rate by 32 % [42]. EDS may be a promising tool for application in dry and desert regions, however it is ineffective for operating in a rainy or damp weather, or with particles of a bigger diameter [43].

Chemical self-cleaning

Using anti-soiling coatings as a supplementary coverage on the front module surface is a passive way to hinder dust accumulation process. Ideally, such material should exhibit high transparency, anti-reflectivity, non-toxicity and durability. Additional expectations also include low production costs and possibility to apply coating at every scale - be it small PV installation or large solar farm. Best candidates for this approach are water-repelling as well as water-dispersing films. Figure 9 illustrated the difference between both films, using the concept of water contact angle (CA).

Hydrophobic surfaces are cleaned after rainfall, since water droplet have high CA and they easily roll off, taking away some of the soil, as presented in Figure 10 [4]. Standard hydrophobic complexes include SiO_2, ZnO, ZrO_2 and Si_3N_4 [45]. Test fields on modules enhanced with SiO_2 coatings showed improvement in working parameters. Module with thin film exhibited 15% and 5% more generated power when comparing it to module without cleaning and module with manual cleaning, respectively [46].

Hydrophilic nanofilms obtained by TiO_2 implementation, have enhanced wettability distinctive self-cleaning properties [5]. Hee et al. analysed possible thickness influence on TiO_2 properties and discovered correlation between lower soiling ratio and coating thickness [47]. Additional research was provided by Isaifan et al. and proved 56 % accumulation reduction in one week for environmental tests in Qatar [48].

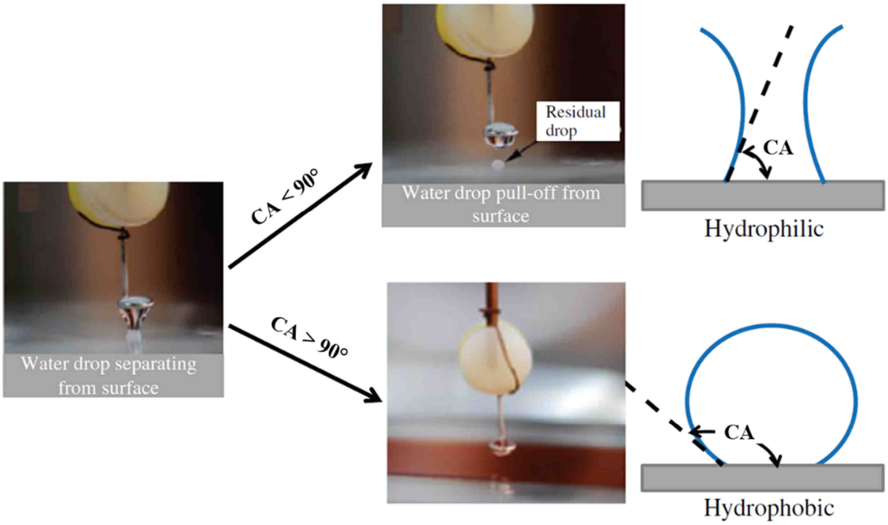

Fig. 9. Water-surface separation and contact angle (CA) for hydrophilic and hydrophobic surface [44]

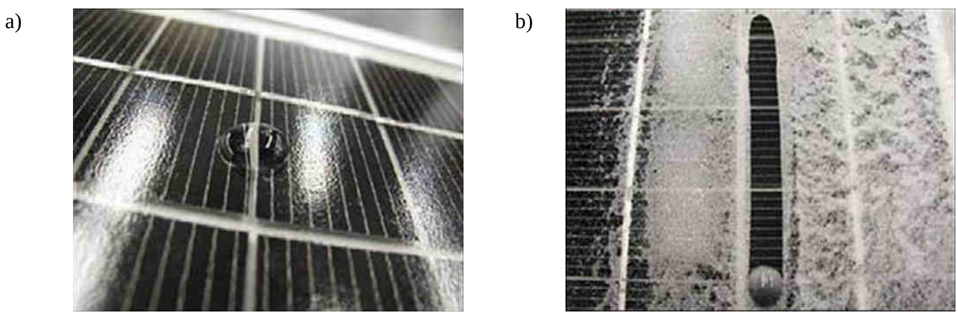

Fig. 10. Hydrophobic SiO_2 film applied on PV module: a) clean surface, b) dirty surface [45]

Cleaning frequency

Customising cleaning cycle to be area-specific helps in maintaining a good balance between cleaning cost and increase in energy yield. The decision for cleaning interval needs to be made based on following factors - deposition rate, dust type, water availability, PV system configuration, labour and necessary equipment cost. It should be underlined that cleaning with higher frequency than needed leads to increase in levelised cost of electricity (LCOE), because it includes more operation and maintenance costs [18]. PV installations located in Middle East seem to experience the fastest dust build-up. This is most likely caused by dry climate with commonly occurring sandstorms. Different regions were gathered in Table 3 with recommended cleaning cycle values.

It should be taken into account that dust settlement on the photovoltaic module surface is an issue irreversibly linked to the location and orientation of the whole installation [61].

Photovoltaic installations located near flowering plants require more frequent cleaning. Therefore, it is worth considering the types of crops near photovoltaic modules. A good solution is to grow sciophilous species, including grasslands rich of pollinator benefits, grasslands with low pollen production [62].

Table 3

Recommendations for cleaning cycle frequency in different locations

Location	Cleaning cycle recommended	Source
Kuwait	Once a month and after every sandstorm	[49]
Egypt	Once a month and after every sandstorm	[50]
Iran	Once a month and after every sandstorm	[51, 52]
Saudi Arabia	Once a month and after every sandstorm	[53-55]
Cyprus	Once every other month	[56]
Thailand	Once every other month	[57]
UK	Once every other month	[58]
Spain	Once every four to five months	[59]
USA	Once every four to five months	[60]

Conclusion

Soiling is a phenomena that occurs in all PV installation over time, but regions with high PM concentration experience this issue at a much higher rate. Since it can drastically reduce expected energy yield, it is a valid concern that needs to be addressed. Varying cleaning methods were discussed as a solution, including natural cleaning, but also mechanical, electrical and self-cleaning techniques. Natural processes, such as wind and rain, help slowing down soil build-up but are never enough to fully put a stop to it. Mechanical approach using manpower seems to be ideal for small private PV installations, where prosumers themselves clean modules. For average-sized and large solar farms, autonomous mechanical cleaning is more convenient, since it cuts down labour expenses and offers flexible cleaning schedule, individually designed for each region. Here a distinction should be made, that PV modules installed in arid climate would call for using more dry brushing techniques with only occasional water sprinkling systems, when it is necessary. This reduces water wastage, which is especially important in dry areas. Electrical cleaning technology utilises electric curtain concept and is a relatively new method for photovoltaics. Since it is still under constant development, there is a great difference between laboratory testing results for efficiency and values obtained for actual installations. Additionally, it needs pointing out that only molecules with smaller diameter can be successfully removed from the module surface by EDS. Chemical self-cleaning approach is characterised by applying thin layer of hydrophobic or hydrophilic substance on the top front PV module surface. It limits the amount of dust which can be deposited in the first place, and then makes it easier for the accumulated soil to slide off - be it after rainfall, or after additional mechanical cleaning. The drawback, however, is in longevity, because such coatings are not permanent and wear off after few years. It therefore calls for reapplication on the whole PV installation. To summarise, there are a few distinct methods to aid photovoltaics industry in combating soiling effects. They have to be chosen correctly for the specific region to maximise possible costs and benefits.

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