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ARTICLE *in* SOLAR ENERGY · SEPTEMBER 2014

Impact Factor: 3.47 · DOI: 10.1016/j.solener.2014.05.030

Arash Sayyah
Boston University

Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 107 (2014) 576–604

SOLAR ENERGY

www.elsevier.com/locate/solener

Energy yield loss caused by dust deposition on photovoltaic panels

Arash Sayyah, Mark N. Horenstein, Malay K. Mazumder *

Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, United States

Received 31 January 2014; received in revised form 8 May 2014; accepted 17 May 2014
Available online 1 July 2014

Communicated by: Associate Editor Bibek Bandyopadhyay

Abstract

Large-scale solar plants are generally located in semi-arid and desert lands where abundant sunlight is available for solar energy conversion. These plants, however, suffer from two major environmental degradation factors: high ambient temperature and high concentration of atmospheric dust. Degradation of solar collectors' performance caused by soiling results in a considerable loss of energy yield in all solar plants of the world. Dust and other particulate accumulation on solar collectors causes transmission loss. This is true with respect to transmission losses in photovoltaic (PV) and concentrated photovoltaic (CPV) systems, and for reflection losses in concentrated solar power (CSP) systems. We present here a brief review of the energy yield losses caused by dust deposition on solar collectors, with particular emphasis on flat-panel photovoltaic (PV) systems. The review includes some of the major studies reported on energy-yield losses on solar plants in operation in several regions of the world. In addition, laboratory-soiling studies are also included. We report on degradation in the performance of solar plants based on the type of solar collectors, geographical location, local climate, and exposure period of the collectors absent any manual cleaning. An analysis of the advantages of cleaning processes that include natural, manual, automatic, and passive methods is presented. Our objective is to provide solar plant designers with a database for predicting anticipated soiling losses in different parts of the world, and for assessing effective cleaning methods for restoring a system's energy yield.

Keywords: Soiling; Dust accumulation; Loss of transmission; Reflectivity loss; Cleaning methods

1. Introduction

Sunlight is an abundant and essentially inexhaustible energy resource but it is not distributed evenly on the earth's surface. Low latitude, arid and semi-arid areas, within 35°N to 35°S, receive the highest direct normal irradiance (DNI). For instance, the Mojave Desert (latitude: 35°N) in southwestern United States, and the Negev Desert (latitude: 30.5°N) in southern Israel receive 1920 kW h/m^2/year and 2007 kW h/m^2/year, respectively (NASA Solar Insolation, 2008). Seven of the worlds deserts, located between these two latitudes, are able to meet the energy needs globally with solar power generation technologies, including photovoltaic (PV), concentrated photovoltaic (CPV), and concentrated solar power (CSP) systems. A recent review (Wu, 2011) reports the mission of an initiative called Desertec to derive electrical energy from solar radiation available in Middle Eastern and North African (MENA) countries to meet major power requirements and to supply up to 15% of the electricity demand of Europe by 2050.

Notwithstanding the fact that deserts and arid zones offer an enormous potential for solar energy harvesting that significantly exceeds current market needs, operation of large-scale PV and CSP plants face substantial challenges. One of the main challenges is the energy yield loss caused by dust accumulation on the optical surfaces

* Corresponding author. Tel.: +1 617 353 0162.
E-mail address: mazumder@bu.edu (M.K. Mazumder).

http://dx.doi.org/10.1016/j.solener.2014.05.030
0038-092X/

of solar energy conversion systems such as PV modules and solar mirrors.

The so-called “soiling” effect, referring to particulate contamination of the optical surfaces, has been found to have a significant deteriorating impact on energy yield due to the absorption and scattering losses of the incident light. Fig. 1 shows daily output power losses in different parts of the world caused by dust accumulation on solar collector surfaces. Although these regions receive high solar irradiance (NASA Solar Insolation, 2008), yet dust accumulation has a detrimental effect on the performance of solar collectors.

Soiling includes not only dust accumulation, but also surface contamination by plant products, soot, salt, bird droppings, and growth of organic species, adversely effecting the optical performance. Major performance-limiting factors other than soiling include temperature effects (primarily in monocrystalline silicon and multicrystalline silicon PV modules), high relative humidity (RH), high wind speed, corrosion, and delamination of the energy conversion devices. Dust deposition on solar collector surfaces depends upon two major factors: (1) location of the solar plants and (2) site’s local environmental conditions (i.e. climate) (Mani and Pillai, 2010). Relevant dust properties include size and charge distribution, material composition, shape, surface energy, and biological properties. Environmental factors include the surrounding vegetation and soil

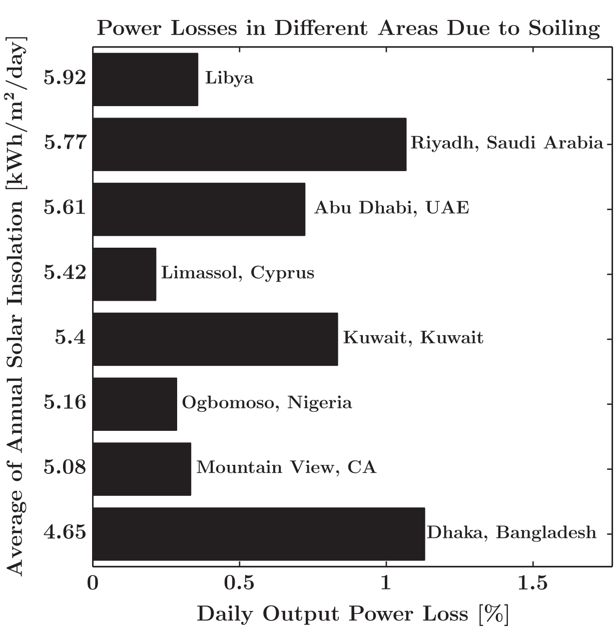

Fig. 1. Daily power loss of solar plants in different parts of the world: Dhaka, Bangladesh (latitude: 23.7°N) (Rahman et al., 2012), Mountain View, CA (latitude: 37.4°N) (Lam et al., 2009), Ogbomoso, Nigeria (latitude: 8.1°N) (Sanusi, 2012), Kuwait, Kuwait (latitude: 29°N) (AlBusairi and Möller, 2010), Limassol, Cyprus (latitude: 34.6°N) (Kalogirou et al., 2013), Abu Dhabi, UAE (latitude: 24.5°N) (Hanai et al., 2011), Riyadth, Saudi Arabia (latitude: 24.6°N) (Salim et al., 1988), and Libya (latitude: 27°N) (Mohamed and Hasan, 2012). (*Note:* The data on power loss, taken from different reports, do not represent annual average loss.)

type as well as climatological characteristics, i.e., frequency of dust storms, precipitation, wind speed/direction, ambient temperature, and relative humidity. Accumulation of dust on the collector surface depends upon the rate of deposition and the rate of removal by wind.

Atmospheric dust concentration decreases exponentially as a function of altitude except under the dust storm conditions. Thus both orientation, such as tilt and height of the solar collectors make a significant difference in energy yield loss. Degradation is reduced if PV panels are installed at a high elevation to minimize dust deposition. Elevation of the solar collectors is often limited by the structural support needed against high-speed wind and the need of convenient cleaning and other maintenance requirements (Thornton, 1992).

Soiling studies have been conducted to determine dust accumulation rate as a function of soiling parameters such as location, wind speed, atmospheric dust concentration, exposure time between cleanings, and the rate of precipitation. These studies are conducted with collectors being cleaned on a regular basis, performing a comparative study while other(s) are left un-cleaned. The results provide the relative soiling loss as a function of exposure period; the longer the exposure period, the more the energy-yield loss without cleaning. In the laboratory soiling studies, dust deposition density has been correlated with soiling losses, with a definitive correlation between power output losses vs. accumulated dust concentration density on the surface (in g/m^2). Most of the field-studies report energy-yield loss vs. exposure time without the dust concentration density and the particle size distribution.

We also report here on the effectiveness of natural precipitation and manual cleaning techniques in removing deposited dust from collector surfaces. As depicted in Fig. 2, these processes include manual, automatic, and passive methods for maintaining a clean optical surface. Passive methods include modification of collector surfaces to aid cleaning or to minimize surface adhesion of the dust layer. Different methods of manual cleaning with water are reviewed along with newly developing automatic cleaning methods, which are still in the development stage. The advantages and drawbacks of these methods are compared.

Apart from soiling losses associated with terrestrial systems, similar problems related to dust accumulation on solar panels used for powering devices in lunar and Mars missions are also identified. The effect of dust accumulation on the performance loss of solar cells installed on the Mars Pathfinder, was simulated for 30-day and two-year mission periods (Landis, 1996). For the baseline and worst case scenarios assumed in this study, power losses of about 6% and 30%, respectively, were predicted for the 30-day mission period, and 75% and 85% for a two-year mission period.

The major emphasis of this review is to study the loss of energy-yield of PV plants as a function of (1) angle of inclination, (2) particle size distribution, (3) radiation wavelength, (4) environmental parameters such as relative humidity, wind velocity, and frequency of dust episodes,

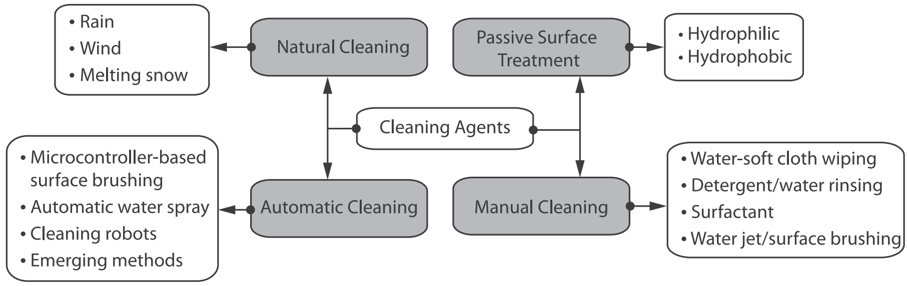

Fig. 2. Different cleaning methods for removing dust from solar collectors.

and (5) natural and manual cleaning. The possible impact of automatic cleaning methods on the efficient restoration of power is examined.

2. Dust deposition

2.1. Effect of inclination angle

Tilt angle (β) of the PV modules has a strong influence on dust deposition (Garg, 1974; Sayigh et al., 1985; Nahar and Gupta, 1990; Pande, 1992; Hegazy, 2001; Elminir et al., 2006; AlBusairi and Möller, 2010; Cano, 2011; Hee et al., 2012; Appels et al., 2012). For collectors installed at a fixed angle, i.e. not equipped with a solar tracking system, dust accumulation decreases when inclination angle increases from horizontal (0°) position to vertical (90°).

When the tilt angle (β) is 0°, the entire surface of the panel faces upward. Since gravitational settling is the primary mechanism for dust deposition, the dust accumulation rate is highest under this condition. The surface area of a solar collector projected upward decreases as the tilt angle β increases from 0° to 90°. When the PV module is positioned vertically, the primary deposition mechanism of soiling is the diffusion of particles. Since the gravitational soiling rate is proportional to d^2 where d is the equivalent diameter of the particle, one can see that the larger the particle size, the higher the deposition velocity. Thus most of the particles depositing on a horizontal surface would be large, with fewer fine particles. In contrast, diffusion, including turbulent diffusion, is inversely proportional to d; hence dust deposited on a vertical surface would be comprised predominantly of fine particles.

The typical fixed panel has its tilt angle set at $\beta = (L \pm 10)^\circ$, where L is the latitude of the solar plant site. The surface area of the collector projected upward would be $A \cos \beta$ where A is the area of the solar collector. Both the mass concentration density in (g/m^2) and the particle size distribution of the deposited particles will depend upon the angle β. In general, both gravitational settling and diffusion are the primary deposition mechanisms under clean conditions.

The impaction of airborne dust having a wind velocity component perpendicular to the surface of the collector results in the collection of large particles. In such cases, there will be additional dust deposition caused by the impaction of particles aided by the electrostatic forces of adhesion if the particles are charged. In arid zones, most of the dust particles gain a significant magnitude of electrostatic charge during their erosion from the soil.

The wind also causes removal of the deposited dust. The dust removal rate at a relatively high wind speed will be more effective at a high tilt angle. Removal of the deposited dust also depends upon the particle diameter d and the microstructure of the dust layer. A thin layer of dust deposited on a horizontal surface cannot easily be removed by wind, even at a relatively high velocity (50 m/s). The removal force, which is limited by the boundary-layer air velocity, has been found to be ineffective for particles with $d < 50$ μm when the free stream velocity is less than 50 m/s. The primary reason for this low inefficiency of wind removal is that the adhesion force of the particles with the surface is proportional to d while the removal force is proportional to d^2 in the case of wind force. When d is small, the adhesion force is higher than the removal force (Hinds, 1999).

Because of gravitational forces, some of the larger particles can roll off the panel's surface or move to the lower parts as the tilt angle increases. Cleaning of the panels by rain and wind is also dependent upon the tilt angle and orientation of surfaces with respect to wind direction. As accumulation of large particles decreases with increasing tilt angle, the relative concentration of fine particles increases on tilted surfaces. In a study performed in Minia region, Egypt (Hegazy, 2001), it was observed that the surface densities of collected particles having small mean diameters (<1 μm) were higher on panels having high inclination angles, while coarser dust particles (mean diameter of 3 μm) deposited with higher proportions on low-inclined panels.

2.2. Attenuation of sunlight by dust layer

The soiling impact on the transmittance of sunlight by dust layer deposited on glass plates exposed to the outdoor environment in Thar desert, India, from May 1986 to December 1987 was studied by Nahar and Gupta (1990). Maximum transmission reduction in the month of May, when the area experiences frequent dust storms, was recorded 1.87%, 4.62%, and 6.28% for 90°, 45°, and 0° tilt angles, respectively, for the daily-cleaned glass specimens. For the samples cleaned weekly, the maximum reduction in transmittance was observed in the April–May period with 5.67%, 13.81%, and 19.17% for 90°, 45°, and 0° inclined samples, respectively. Fig. 3 summarizes the soiling data for different cleaning cycles and time intervals. As can be observed in Fig. 3, glass samples experienced significantly higher losses in the period July 21, 1987–September 15, 1987 (56 days) than the ones in the period January 20, 1987–July 18, 1987 (180 days) although the exposure time was approximately three times shorter. The reason is attributed to the restoring effect of heavy rainfall events in the 180-day period that increased the transmittance while the area experienced scarcity of rain precipitation in the 56-day period.

In addition to the tilt angle, the effect of azimuth angle was simultaneously considered by Elminir et al. (2006). Several glass samples were mounted on racks at different azimuth and tilt angles and exposed to the outdoor environment in Minia, Egypt (latitude: 28°N). The maximum reduction in light transmission was found to be 27.62% for the horizontal panel. However, transmission loss was only 4.94% for the glass sample tilted at 90° and facing southeast. The transmittance reduction for different orientations and tilt angles are plotted in Fig. 4, which shows the effect of tilt and azimuthal angles. Furthermore, among PV samples exposed outdoors with different positions during the period of December 2004–June 2005, the PV sample tilted at 45° and facing south exhibited a higher power yield that was independent of season compared with other PV samples at different tilt angles and orientations. The output power loss rate of the PV sample tilted at 45°S was found to be 17.4% per month.

Qasem et al. (2012) exposed south-facing glass samples at various tilt angles under outdoor conditions for one month in Kuwait. A non-uniformity index defined as transmittance values at the top, middle, and bottom of the samples. Non-uniformity of the vertical sample was found to be 0.21%, while the sample tilted at 30° showed a 4.39% non-uniformity between the three sections. This observation suggests non-uniform dust deposition as a function of tilt angle.

Lorenzo et al. (2013) investigated the impact of non-uniform dust deposition pattern on PV arrays in a 2 MW

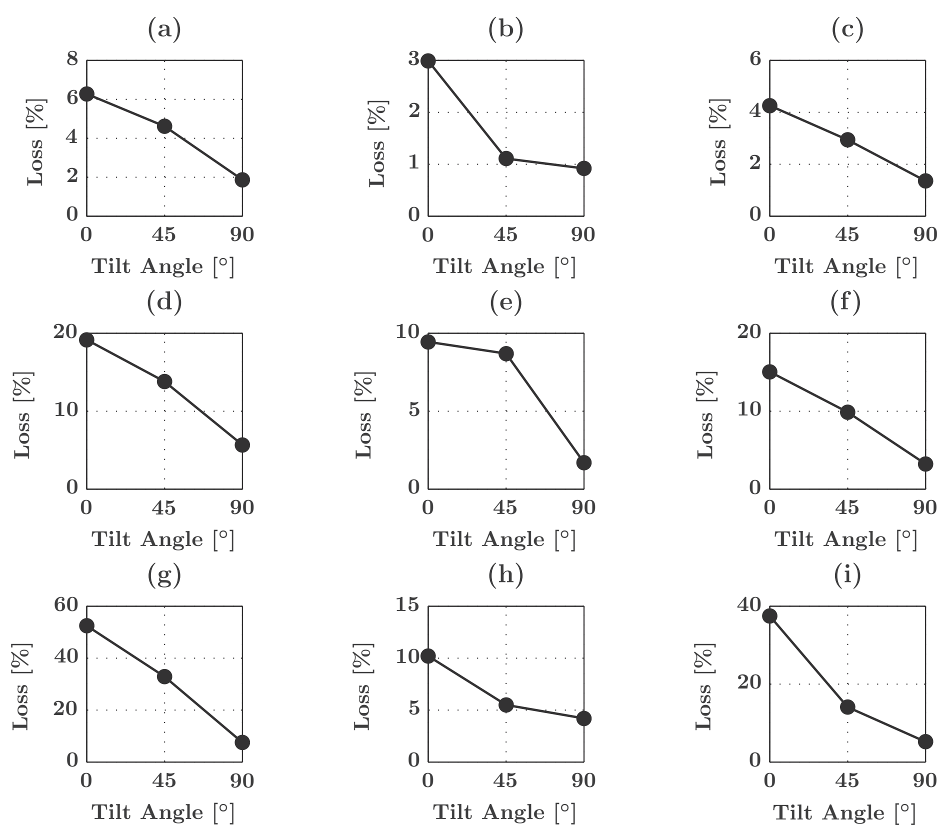

Fig. 3. Light transmission losses for glass samples tilted at 0°, 45°, and 90°, exposed in Thar desert, India from May 1986 to December 1987 (Nahar and Gupta, 1990): (a) maximum transmission loss for daily cleaned samples recorded in May, (b) minimum transmission loss for daily cleaned samples recorded in January, (c) annual average transmission loss for daily cleaned samples, (d) minimum transmission loss for weekly cleaned samples recorded in April–May period, (e) minimum transmission loss for weekly cleaned samples recorded in January–March period, (f) annual average transmission loss for weekly cleaned samples, (g) transmission loss of never manually cleaned samples in June 11, 1986–December 10, 1986 (182 days), (h) transmission loss of never manually cleaned samples in the period January 20, 1987–July 18, 1987 (180 days), and (i) transmission loss of never manually cleaned samples in the period July 21, 1987–September 15, 1987 (56 days).

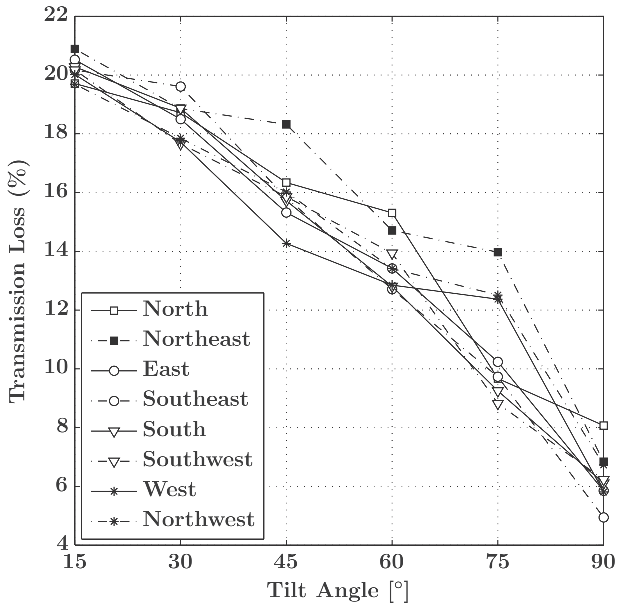

Fig. 4. Transmission reduction by dust accumulation for sample glass specimens with different orientation and tilt angles exposed to the outdoor environment in Minia, Egypt (Elminir et al., 2006). The inset in the figure shows the direction to which the glass samples were facing.

PV park in southeastern Spain. It has been observed that dusty modules have significantly lower operation voltage than the less dusty or clean ones in the same string. Partially-shaded cells act as loads to clear cells connected in series. Consequently, more output power losses occur in the formation of hot spots. Infrared (IR) images taken from the array showed that hot spots formed in areas with higher dust concentration with up to 23 °C higher compared to that of the surrounding panel surface. In long-term exposure, these hot spots cause the thermal degradation of the PV arrays.

3. Effects of dust properties on transmission losses

3.1. Particle size

The effect of the physical and chemical properties of dust particles on the performance of PV modules was studied by El-Shobokshy and Hussein (1993). In their work, carbon, cement, and three types of limestone particles having median diameters of 5, 10, 50, 60, and 80 μm were tested. The dust particles were deposited on a PV surface at a controlled surface-mass density, and the power output was measured. The results showed that finer particles have a more deteriorating effect on cell performance than coarser particles at the same surface mass density of 25 g/m^2. The results also show that normalized power output in the case of cement and carbon particles dropped by 40% and 90%, respectively. This significant difference can be attributed to the fact that finer particles deposited on the cover glass surface have more specific surface area compared to that of the larger particles, causing more scattering losses. The light extinction coefficient due to scattering losses is directly proportional to the projected area of the particles when the particle diameter d is larger than the wavelength (λ) of light.

Gaier and Perez-Davis (1991) investigated the effects of dust deposition on solar panels related to their use on the exploration of Mars and the moon. They examined the role of particle size of on the transmission losses using transparent glass substrates using simulated Martian dust. Four different particle diameter ranges were used: 10, 30, 60, and >75 μm. Using a wind tunnel and a dust loading device, the deposition of dust provider on the glass plates was studied as a function of particle size, wind velocity, and the angle between the direction of wind velocity and the front surface plate of the substrates. The results show that both particle diameter and wind velocity play major roles on the mass density of deposition and corresponding attenuation of light. Surface mass density of the dust deposition was negligible at a high wind velocity. At a lower wind velocity (<24 m/s), however, particles of 30 μm size had 12% and 20% more deteriorating effect at 45° and 90° angles between the direction of flow and the impacting surface, respectively, compared to large size (>75 μm) particles.

3.2. Effects of wavelength on the transmission and reflection losses

Variation in transmittance loss due to scattering, absorption, and reflection of light caused by dust deposition was studied as a function of the wavelength of radiation by several researchers in laboratory environments. Hasan and Sayigh (1992) used glass plates with 4-mm thickness mounted horizontally in a test chamber for collecting test dust samples. The transmittance losses were measured for different dust accumulation densities and plotted as a function of two wavelengths 540 and 720 nm. They observed that light transmittance decreased at all visible wavelengths as the dust accumulation density increased. The results for only two wavelengths, 540 nm and 720 nm, are shown in Fig. 5.

The role of wavelength in the transmittance and reflectance efficiency variations of glass samples coated with dust was investigated by Al-Hasan (1998). In his studies, the wavelength ranged from 190 to 900 nm, because the majority of PV modules are not responsive outside this range. The transmittance of clean and dusty glass samples at different dust concentration densities up to 15.6 g/m^2 was examined using a spectrophotometer. At all wavelengths, the transmittance decreased as the dust concentration density of a sample increased. The transmittance decreases as the wavelength increases for a particular dusty glass sample. Table 1 shows the light reflectance at different wavelengths and dust concentration densities: reflectance increases as the dust deposition density increases, although this increase is more prominent at longer wavelengths. Because the color of the examined dust was red or brown,

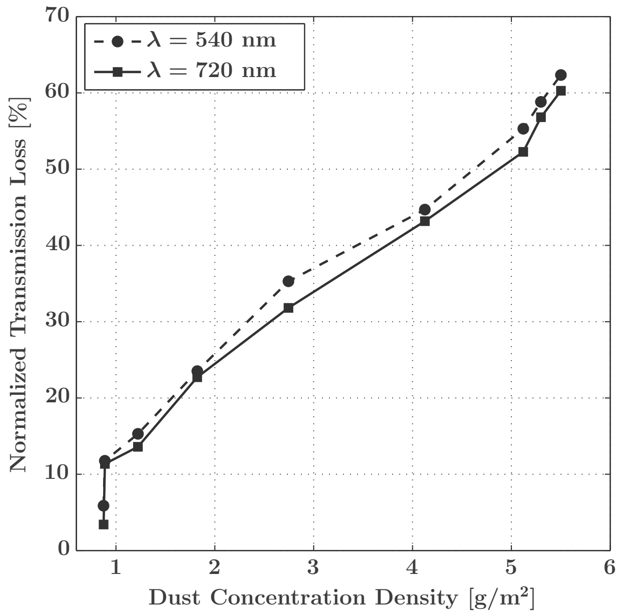

Fig. 5. Normalized transmission losses of dusty glass samples with respect to the clean samples with 88% and 85% transmissions at 540 and 720 nm, respectively (Hasan and Sayigh, 1992).

shorter wavelengths were absorbed and longer ones reflected.

The experimental data showing the variation of reflectance as a function of wavelength can also be interpreted in terms of transmission losses, since the increase of reflected light intensity is the result of back-scattered light from the deposited particles. The effect of incidence angle in the transmission of the glass samples was further investigated for different dust concentration densities up to 2.24 g/m^2. The light transmittance decreased as the incidence angle increased.

As shown by Qasem et al. (2012), transmission losses are much higher at smaller wavelengths (300–570 nm) than at higher wavelengths. Scattering losses increase when particle size is comparable to the wavelength of light. Furthermore, the wavelength dependency of transmission loss vanishes for dust concentration densities higher than 19 g/m^2. This point is also indicated in Al-Hasan (1998). When the surface mass density of particles is small, each particle can be considered as a single scattering object. When the mass density increases to form a thick layer, multiple scattering is involved and the dust layer acts as a film having a rough surface. The transmission losses can be analyzed by optical modeling.

4. Environmental factors

4.1. Dust events

Dust accumulation on solar collectors located in deserts and in semi-arid zones vary widely; these areas also experience dust storms that are not evenly distributed over the year. Studies by Goossens and Offer (1995), performed in Sede Boqer, Israel show that dust accumulation during the day is considerably higher than at night. In the same study, accumulated aeolian dust at night was reported to be significantly coarser than that of dust deposited during the day. Given a particular time of the year and geographical location of the site, the occurrence of dust episodes was predictable to some extent based on the availability of meteorological data collected over the years. For instance, based on 37 years of visibility observations near Beer Sheba, Israel in the Negev desert, more than 89% of the total annual dust was found to accumulate during the "high dust season", between December and May, with a maximum in March (Dayan et al., 2008).

PV installations located in different parts of the world are subject to environmental degradation caused by high dust deposition rates at certain times of the year. For example, (1) Abu Dhabi, UAE experiences nearly seven sandstorms per year, three of them often happen in March (El-Nashar, 2003), (2) Minia region, Egypt has dust storms that occur frequently during the months of April and May (Hegazy, 2001), (3) in Kuwait, maximum amount of dust deposition occurs during the months of June and July and minimum amount occurs in the months of October–December (Sayigh et al., 1985; Hasan and Sayigh, 1992), and (4) in Ogbomoso, Nigeria (Sanusi, 2012; Gwandu and Creasey, 1995), the maximum amount of dust accumulation has been reported in the December–March time period when a dry and dusty wind, called Harmattan, blows.

4.2. Effect of tracking

Most large-scale PV modules are installed at fixed tilt angle. Photovoltaic systems equipped with solar trackers can be used to produce maximum power output and to minimize dust accumulation. Tracking also can provide panel orientation that can be used for convenient cleaning and for stowing the panels facing down at night and during dust storms. Promising results have been reported related

Table 1
Reflectance of dusty glass samples for different dust concentration densities and wavelengths (Al-Hasan, 1998).

Wavelength (nm)	Dust deposition density (g/m^2)							
	Clear (%)	0.7 (%)	2.5 (%)	3.5 (%)	7.3 (%)	8.8 (%)	9.5 (%)	14.6 (%)
400	4	5	9	10.5	11	2	12.5	12.5
500	4	5.5	12.5	14	16	20	21	22
600	4	5.5	14	17	19.5	27	28	32
700	4	5.5	14	17	20	27	30	34
800	4	5.5	14.5	17	20.5	29	30.5	36

to the dust accumulation issue. Variable tilt/azimuth angle in solar systems with tracking capabilities can clearly make the cleaning role of gravitational forces or natural cleaning agents more convenient in removing deposited particulates from collectors' surfaces. In an experimental set up in Hermosillo, Sonora, Mexico (Cabanillas and Munguia, 2011), the relatively low dust accumulation loss after 20 days of exposure was attributed to the solar tracking system, compared to fixed tilt-angle PV systems. In another study, four identical PV systems were exposed to the outdoor environment near Riyadh, Saudi Arabia for a period of one-year (Salim et al., 1988). Test results showed that energy output gain of the single axis solar tracking system varied between 16% and 21%, with an average of approximately 18% per month, compared to the array at a fixed tilt angle of 24.6° (site's latitude). Furthermore, the performance of the two-axes tracking system exhibited an approximate increase of 2% power output compared to the single-axis tracking system. These differences are attributable to less dust accumulation and more sunlight absorption in solar tracking systems with respect to fixed modules. Tracking systems, however, might show slightly lower power conversion efficiency due to the high temperature of the solar cell and exposed to high DNI as they always track the sun (Al-Busairi and Al-Kandari, 1987).

4.3. Relative humidity

In semi-arid and desert regions, rainfall is rare; precipitation may occur during a short period of the year but can have high relative humidity and can form dew in the early morning hours in some locations. High relative humidity (RH) promotes the adhesion of dust and the formation of sticky dust layers on PV surfaces. High RH also causes more absorption of solar radiation by the enhanced concentration of water vapor in the atmosphere, thereby causing a decrease in solar irradiance. Deserts near the ocean may have dense fog in the morning, reducing DNI significantly. Furthermore, over the course of time at a high humidity, biological species may start to grow on the PV modules. These in turn trap fine dust particles (Haeberlin and Graf, 1998). Occasionally, these areas experience light rain, often called "dusty rain", that scavenges the airborne dust particles and form sticky mud patches on the surfaces of the collectors.

Comparing results obtained from two installation sites located in Cleveland, Ohio (humid location) and Phoenix, Arizona (semi-arid location) (Hoffman and Maag, 1980b), it was observed that high RH plays a significant role in forming stronger bonds between dust particles and silicon-rubber module surfaces, as highlighted by Mekhilef et al. (2012). As DNI decreases, I_{sc} decreases linearly with irradiance level and since V_{oc} is not a strong function of irradiance, the efficiency of a solar cell decreases as the humidity increases.

Touati et al. (2012) have shown that the impact of RH is dependent upon the type of PV module. In their studies, two commercially available monocrystalline (c-Si) and semi-flexible amorphous silicon (a-Si or a-Si:H) PV modules were exposed to the outdoor environment in Qatar. It was shown that when temperature or relative humidity increased, both PV modules experienced a drop in efficiency.

The effect of RH on the visible solar irradiance in the tropical Savannah region of Sudan (latitude: 13.6°N) and its impact on the performance of monocrystalline silicon PV module was investigated by Gwandu and Creasey (1995). It was observed that when the wind speed is high (8:00–11:00 am), the RH was low. This trend reversed when the wind speed decreased (14:30–17:00 pm). The irradiance reaching the cell was shown to be a nonlinear function of RH; DNI decreased monotonically as RH increased for RH values higher than 22%. High wind velocity was found to reduce RH in the vicinity of the PV modules and decreased cell temperature, consequently increasing cell efficiency.

4.4. Bird droppings

One of the problems affecting the performance of PV installations is that of bird droppings. This organic material blocks incident sunlight from reaching the cell. The affected areas remain shaded until cleaned, thereby creating potential zones of hot spots as the cells underneath act as load to the current output from the rest of the series-connected cells. Metal frames are also subject to corrosion because of bird feces. In semi-arid areas and in residential applications, bird droppings on PV modules can be a limiting factor in the PV cell's performance (Appels et al., 2012). According to Hammond et al. (1997), who investigated the soiling effect on three different solar installations in Phoenix, Arizona, the effect of bird droppings on module performance was found to be more severe than that due to dust deposition. In deserts, dust accumulation is considered as the predominant factor in reducing the panel performance, but at off-shore installations, bird nesting and droppings are the most frequent limiting factors (Lamont and Chaar, 2011). Methods such as bird control netting, bird spikes, audible bird scares, low-current electric barriers, and nontoxic bird control products (Ballinger, 2001) are used widely in practice. Some of the applied methods may become nonfunctional after a time, because birds can quickly adapt themselves to these fictitious hazards. Satisfactory results were reported in studies by Cano (2011), in which metal spikes were used to keep the birds away from PV modules.

5. Experimental data on soiling losses

5.1. Laboratory soiling studies

In laboratory soiling studies, a controlled environment test chamber equipped with a solar simulator to provide simulated sunlight and a pyranometer to measure and control irradiance is used for simulating field conditions. The method is advantageous since dust depositions can be controlled both with respect to the particle size distributions and surface mass concentrations.

Figs. 6–10 provide the results of some of the studies (El-Shobokshy and Hussein, 1993; Kaldellis et al., 2011; Sulaiman et al., 2011; Jiang et al., 2011; Molki, 2010), respectively, focused on laboratory soiling studies of PV modules and glass cover plates, and the effect of dust deposition on their performance. As can be seen in Fig. 6, carbon particulates, found particularly in urban areas due to incomplete combustion of fuels in industrial plants and automobiles, have severe deteriorating effect on the performance of solar collectors. Such detrimental effect caused by soot particulates were also observed in outdoor studies (Liqun et al., 2012; Asl-Soleimani et al., 2001). Since carbonaceous particles arising from anthropogenic sources and forest fires are generally fine particles, they can travel a long way. Three common air pollutants with relatively high light-absorption coefficients are red soil containing oxides of iron, limestone, and carbon-based ash (combustion products). Attenuation of light caused by these particles with different concentration was studied by depositing test dust on polycrystalline silicon PV panels (Kaldellis et al., 2011). The results are depicted in Fig. 7.

Fig. 8 shows the effect of two types of test dusts: powdered dry mud and talcum powder with thicknesses 41 μm and 101 μm, respectively, deposited uniformly on different cover plates of PV modules. The subsequent soiling losses were determined using a clean PV module without any plastic covering as the control. Power losses

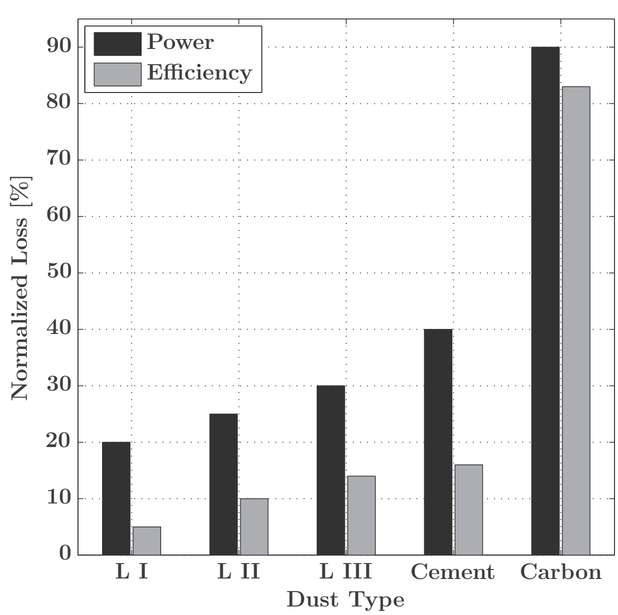

Fig. 6. Normalized power and efficiency losses of PV panel caused by deposition of three different sizes of limestone particles (denoted as L I, L II, and L III), cement, and carbon with dust concentration density of 25 g/m^2 (El-Shobokshy and Hussein, 1993). The significant losses of carbon particles compared to the others is attributable to the its particle diameter of 5 μm.

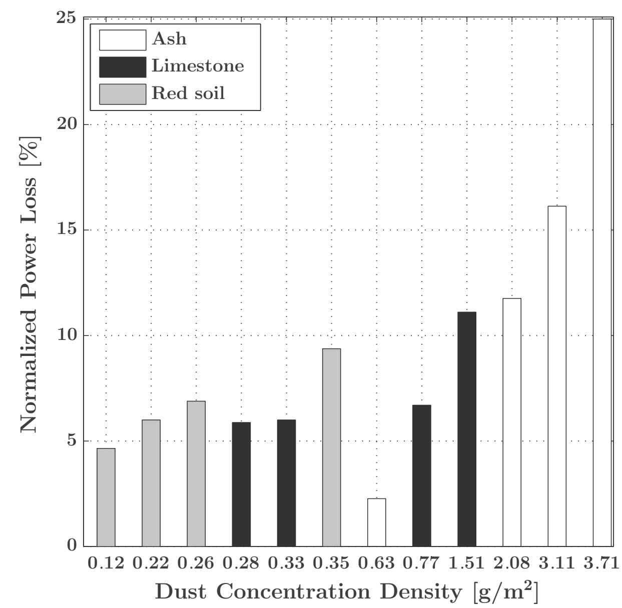

Fig. 7. Laboratory test results for three different dust types: ash, limestone, and red soil with various concentration densities deposited on polycrystalline silicon PV modules (Kaldellis et al., 2011).

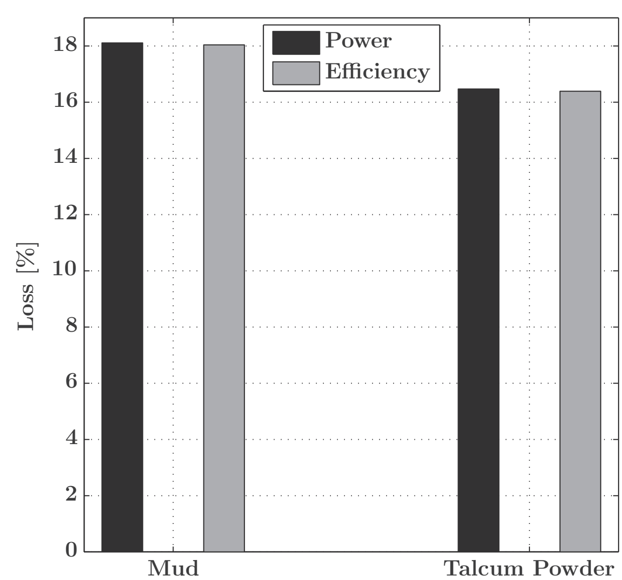

Fig. 8. Power and efficiency losses for dry mud and Talcum powder layers with thicknesses of 41 μm and 101 μm, respectively, deposited on the plastic cover of monocrystalline silicon PV modules (Sulaiman et al., 2011).

for the PV modules with mud and Talcum powder layers reach 18% and 16.2%, respectively. Fig. 9 shows the short-circuit current losses for monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), and amorphous silicon (a-Si:H) PV modules with white glass (low iron content) and epoxy cover plates for a dust concentration density of 10 g/m^2.

To examine the effect of dust on the maximum output power loss of a PV cell, different amounts of ground clay

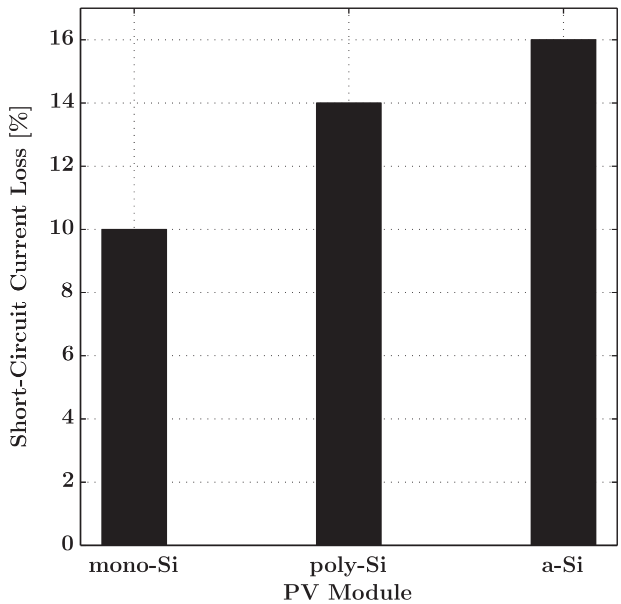

Fig. 9. Losses in short-circuit current for three different PV modules: monocrystalline silicon (mono-Si) and amorphous silicon (a-Si:H) with white glass covers, and polycrystalline silicon (poly-Si) with epoxy cover with dust concentration density of 10 g/m^2 (Jiang et al., 2011).

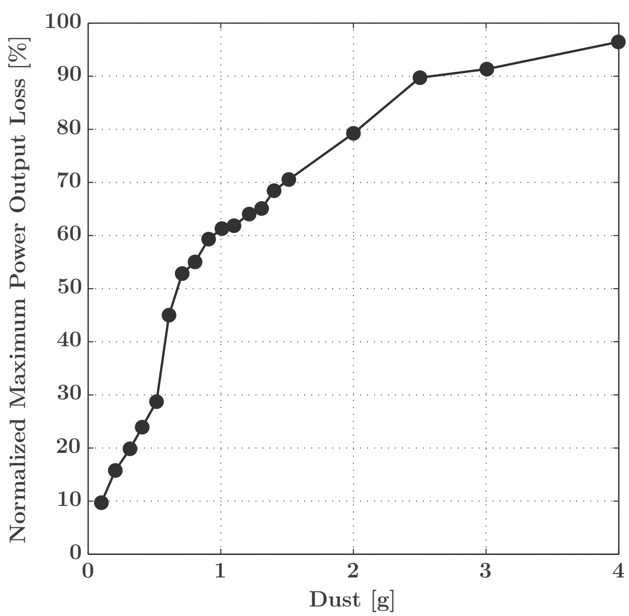

Fig. 10. Losses in maximum power output of a PV cell vs. dust deposition (Molki, 2010).

up to 4 g were deposited on a 12 cm × 8 cm cell (Molki, 2010). Normalized maximum power output loss for different dust depositions is illustrated in Fig. 10. In Fig. 10, the 0.1, 0.2, and 0.3 g depositions are associated with 10.42, 20.83, and 31.25 g/m^2 dust concentration densities, respectively. Furthermore, Fig. 10 shows that as dust deposition density increases, the rate of maximum output power loss decreases. Similar behavior of performance loss vs. dust deposition density can be seen in other studies such as (Al-Hasan and Ghoneim, 2005). These studies are discussed in the next subsection.

5.2. Outdoor soiling studies

Table 2 provides a summary of soiling studies of outdoor exposure of solar collectors, mainly PV modules and the effect of dust deposition on their performance. For each of the studies listed in the table, (1) test location, (2) environment, (3) general climate of installation site, (4) front surface of the solar collector, (5) tilt angle, (6) solar collector type, (7) exposure period, (8) affected output(s) measured, and (9) maximum recorded loss are given. In case of multiple data points in a study, only a few are listed to show the trend. The majority of the experimental studies used glass cover plates; the data presented here also include polyvinyl chloride (PVC), low-density polyethylene (LDPE), and Tedlar® (a product of DuPont containing fluoropolymer) used as the front cover plate of the solar collectors. Most of the soiling loss studies have been reported for flat plate PV systems which include monocrystalline silicon (c-Si), multicrystalline silicon (mc-Si), copper indium gallium selenide (CIGS), cadmium telluride (CdTe), polycrystalline silicon (poly-Si), and amorphous hydrogenated silicon (a-Si or a-Si:H) PV modules. In Table 2, T, I_{sc}, η, P_{out}, and V_{oc} denote transmission, short-circuit current, efficiency, output power, and open-circuit voltage, respectively. To distinguish various climate conditions, the Köppen system, one of the most frequently chosen climate classification systems, is used. The impact of soiling on solar concentrators used for photothermal plants and concentrated photovoltaic (CPV) modules is also presented. Different geographical parts of the world with diverse climatological conditions including deserts, semi-arid, and temperate climate zones have been covered from the available literature.

In general, most natural soiling studies on dust deposition are carried out with one module cleaned on a regular basis, and others left unattended to collect dust. Energy-yield losses vs. time are reported based on experimental data obtained from the un-cleaned and routinely cleaned collectors. El-Shobokshy et al. (1985) emphasizes that solar collector exposure time in the natural environment is less important than the amount of dust deposited on the collector surface. The latter should be correlated to the efficiency degradation. The exposure time does not provide quantitative information on light attenuation vs. dust deposition, but it provides important information about the dust deposition rate at the site's geographical location that is not otherwise available. Unfortunately, many studies in the literature omit surface mass density of dust in g/m^2 as a function of exposure time and the composition of the particles.

Performance degradation of PV modules as a function of dust concentration density in outdoor environments (in lieu of exposure time) has been studied by Al-Hasan and Ghoneim (2005). They installed two polycrystalline PV modules at 30° tilt angle on the roof of a building in

Table 2
Natural soiling studies performed in different parts of the world.

Reference	Location (Lat.,Long.)	Environment	Climate	Front surface	Tilt angle, orientation	Collector type	Exposure period	Affected output(s)	Max. loss (%)
Hottel and Woertz (1942)	Cambridge, MA, USA (42.37°, –71.11°)	Industrial/ residential	Humid subtropical/humid continental	Glass	30°, South	Heat collector	53 days	Heat	4.7
Garg (1974)	Roorkee, India (29.83°, 77.88°)	Urban	Continental	Glass	60°, South 40°, South 20°, South	Heat collector	30 days	T	10 16.7 50
Maag (1977)	Berkeley Springs, WV, USA (39.6255°, –78.22°)	Rural	Mild	Polycarbonate 1 Polycarbonate 2 Silicone	45°, South	PV module	1 year	I_{sc}	10 12 7
Sayigh et al. (1979)	Riyadh, Saudi Arabia (24.71°, 46.72°)	Urban	Desert	Polyethylene	25°, South	mono-Si PV module	1 month	η	25
Nimmo and Said (1979)	Dhahran, Saudi Arabia (26.28°, 50.11°)	Urban	Desert	Glass	26°, South	PV module	2 months	P_{out}	15
Hoffman and Maag (1980b)	Pasadena, CA, USA (34.14°, –118.14°)	Urban	Hot-summer Mediterranean	Poly (dimethyl siloxane) Proprietary silicone Soda lime glass Brosilicate glass Alumino silicate glass Polyvinyl flouride Acrylic	45°, South	PV module	150 days	T	37
Hoffman and Maag (1980a)	Cleveland, OH (41.5°, –81.69°)	Suburban Suburban Industrial	Continental	Silicone rubber Glass Silicone hardcoat	40°, South	PV module	83 days	I_{sc}	8 6 23
	New York, NY (40.71°, –74°)	Urban	Humid subtropical	Silicone rubber Glass Silicone hardcoat	45°, South	PV module		I_{out}	43 12 43
Khoshaim et al. (1984)	Riyadh, Saudi Arabia (24.71°, 46.72°)	Rural	Desert	Glass	Sun tracker	PV module	30 months	I_{sc}	35
Sayigh et al. (1985)	Kuwait, Kuwait (29.36°, 47.97°)	Urban	Desert	Glass	30°, South	Sheet	27 days	T	50
El-Shobokshy et al. (1985)	Riyadh, Saudi Arabia (24.71°, 46.72°)	Urban	Desert	Glass	Sun tracker	CPV module	1 month	I_{sc} P_{out} η	28.6 30.6 55
Al-Busairi and Al-Kandari (1987)	Kuwait, Kuwait (29.36°, 47.97°)	Urban	Desert	Glass	30°, South	PV module	14 months	P_{out}	55
Salim et al. (1988)	Riyadh, Saudi Arabia (24.71°, 46.72°)	Suburban	Desert	Glass	24.6°, South	PV module	1 year	Energy η	32 28.6
Bajpai and Gupta (1988)	Sokoto, Nigeria (12.5°, 4.3°)	Urban	Tropical semi-arid	Glass	12.5°, South	PV module	4 months	P_{max}	60
Ryan et al. (1989)	Eugene, OR (44.03°, –123°)	Urban	Mild	Glass	45°, South	PV module	6 years	I_{sc}	8.4

Nahar and Gupta (1990)	Thar desert, India (27.7°, 72.15°)	Desert	Arid	Glass Acrylic PVC	45°, South	Sheet	20 months	T	4.6 4.8
Said (1990)	Dhahran, Saudi Arabia (26.28°, 50.11°)	Urban	Desert	Glass	26°, South	PV module	6 months	η	60
Yahya and Sambo (1991)	Sokoto, Nigeria (12.5°, 4.3°)	Urban	Tropical semi-arid	Glass	13°, South 0°	PV module	2 weeks	I_{sc}	4.7 6
Pande (1992)	Jodhpur, India (26.23°, 73.02°)	Urban	Semi-arid	Glass	4–48°, South	mono-Si PV module	1 year	I_{sc}	2–17
Som and Al-Alawi (1992)	Isa Town, Bahrain (26.17°, 50.54°)	Urban	Desert	Glass	0° 26°, South	mono-Si PV module	2 months	I_{sc}	41.4 31
Bonvin (1995)	Morges, Switzerland (46.51°, 6.49°)	Urban	Mild	Glass	0°	PV module	1 year	T	22
Becker et al. (1997)	Cologne, Germany (50.93°, 6.96°)	Urban	Temperate-oceanic	Glass	20°, South	PV module	5 years	P_{out}	24
Haeberlin and Graf (1998)	Bern, Switzerland (46.94°, 7.44°)	Industrial	Mild	Glass	30°, South	PV module	4 years	Energy	10
Mastekbayeva and Kumar (2000)	Bangkok, Thailand (13.75°, 100.38°)	Urban	Tropical	LDPE plastic	15°, South	Air heater	30 days	T	13.8
Townsend and Hutchinson (2000)	Davis, CA, USA (38.54°, −121.44°)	Suburban/rural	Hot-summer Mediterranean	Glass	18.4°, South	PV module	2 years	I_{sc}	20
Asl-Soleimani et al. (2001)	Tehran, Iran (35.69°, 51.42°)	Urban, severe air pollution	Cold semi-arid	Glass	45°, South	mc-Si PV module	8 days	P_{out}	43
Hegazy (2001)	Minia, Egypt (28.07°, 30.76°)	Urban	Subtropical	Glass	20°, South 40°, South 60°, South	PV module	30 days	T	21 16 11
El-Nashar (2003)	Abu Dhabi, UAE (24.46°, 54.36°)	Urban	Desert	Glass	N/A	Thermal collector	1 year	T η	33.7 50
Elminir et al. (2006)	Helwan, Egypt (29.84°, 31.33°)	Suburban/industrial	Arid	Glass	15°, Northeast 30°, Northeast 45°, Northeast	mono-Si PV module	7 months	T	20.9 18.9 18.3
Pang et al. (2006)	Hong Kong, China (22.39°, 114.10°)	Urban	Humid Subtropical	Glass	0°	CIGS PV module	3 months	η	16.1
Kimber (2007)	Los Angeles, CA, USA (34.05°, −118.24°)	Urban	Hot-summer Mediterranean	Glass	0°	PV module	1 year	Energy	5.1
Lam et al. (2009)	Mountain View, CA, USA (37.38°, −122°)	Urban	Mediterranean	Glass	0°	PV module	8 months	Energy	80
El-Nashar (2009)	Abu Dhabi, UAE (24.46°, 54.36°)	Rural	Desert	Glass	24°, South	Evacuated tube Heat collector	1 month	T	18
AlBusairi and Möller (2010)	Kuwait, Kuwait (29.36°, 47.97°)	Urban	Desert	Glass	30°, South	CdTe PV module	1 year	Energy	25

(*continued on next page*)

Table 2 (*continued*)

Reference	Location (Lat.,Long.)	Environment	Climate	Front surface	Tilt angle, orientation	Collector type	Exposure period	Affected output(s)	Max. loss (%)
Kaldellis and Kokala (2010)	Athens, Greece (37.98°, 23.72°)	Urban	Hot-summer Mediterranean	Glass	30°, South	poly-Si PV module	2 months	Energy	6.5
Boykiw (2011)	Arava Valley, Israel (30.41°, 35.15°)	Rural	Desert	Glass	30°, South	mono-Si PV module	2 weeks	η	8.7
Cabanillas and Munguia (2011)	Hermosillo, Mexico (29.09°, −110.96°)	Urban	Desert	Plastic Glass Glass	Sun tracker	a-Si mono-Si poly-Si PV module	20 days	P_{out}	14 8.5 5.2
Cano (2011)	Mesa, AZ, USA (33.41°, −111.83°)	Suburban	Desert	Glass	23°, South 33°, South	poly-Si PV module	3 months	I_{sc}	3.75 3.4
Ibrahim (2011)	Arar, Saudi Arabia (30.98°, 41°)	Urban	Continental	Glass	N/A	PV module	10 days	I_{sc} V_{oc}	27.8 8.6
García et al. (2011)	Navarre, Spain (42.81°, −1.65°)	Rural	Continental	Glass	45°, South 0°	PV module	15 months	Optical energy	6 15
Hanai et al. (2011)	Abu Dhabi, UAE (24.46°, 54.36°)	Urban	Desert	Glass	25°, South	a-Si PV module	18 days	P_{out} η	13 5.8
Pavan et al. (2011)	Puglia, Italy (40.79°, 17.10°)	Rural	Mediterranean	Glass	25°, South	mc-Si PV module	8 weeks	P_{out}	6.9
Schill et al. (2011)	Gran Canaria, Spain (27.92°, −15.54°)	Industrial	Oceanic	Glass	N/A	PV module	9 months	η	20
Appels et al. (2012)	Leuven, Belgium (50.88°, 4.70°)	Urban	Mild	Glass	60°, South	PV module	4 months	T	3
Hee et al. (2012)	Singapore, Singapore (1.28°, 103.85°)	Urban	Tropical	Glass	0–90°, South	Sheet	33 days	T	10
Mohamed and Hasan (2012)	Libya (26.33°, 17.22°)	Rural	Desert	Glass	40°, North	poly-Si PV module	4 months	P_{out}	2.5
Rahman et al. (2012)	Dhaka, Bangladesh (23.70°, 90.40°)	Urban	Tropical	Glass	23.5°, South	mono-Si PV module	1 month	I_{sc} P_{out}	33 34
Rehman and El-Amin (2012)	Dhahran, Saudi Arabia (26.28°, 50.11°)	Urban	Desert	Glass	30°, South	poly-Si PV module	1 month	P_{out} η	5.9 5.7
Sanusi (2012)	Ogbomoso, Nigeria (8.13°, 4.25°)	Urban	Tropical	Glass	0°	a-Si PV module	70 days 70 days	P_{out}	25 13
Zorrilla-Casanova et al. (2013)	Málaga, Spain (36.72°, −4.42°)	Residential/ industrial	Hot-summer Mediterranean	Glass	30°, South	PV module	1 year	Energy	20
Liqun et al. (2012)	Taiyuan, China (37.87°, 112.56°)	Urban	Semi-arid	Glass	45°, South 0°	PV module	2 weeks	P_{out}	18.2 32.6
Kalogirou et al. (2013)	Limassol, Cyprus (34.70°, 33.02°)	Urban	Mediterranean	Glass Tedlar Tedlar	31°, South	a-Si, poly-Si, mono-Si PV module	10 weeks	P_{out}	8 14 15 15

Caron and Littmann (2013)	Southern Central Valley, CA, USA (37.42°, −120.59°)	Agricultural	Desert	Glass	25°, South	CdTe PV module	16 months	I_{sc}	8.6
	Carrizo Plain, CA, USA (35.11°, −119.47°)	Agricultural	Arid				10 months		5
	Colorado Desert, CA, USA (32.15°, −112.55°)	Rural	Arid				6 months		2.8
Adinoyi and Said (2013)	Dhahran, Saudi Arabia (26.28°, 50.11°)	Urban	Desert	Glass	26°, South	poly-Si	8 months mono-Si PV module	P_{max}	45.4 49
Piliougine et al. (2013)	Málaga, Spain (36.72°, −4.42°)	Residential/industrial	Hot-summer Mediterranean	Glass	21°, South	poly-Si PV module	10 months	I_{sc}	12.5

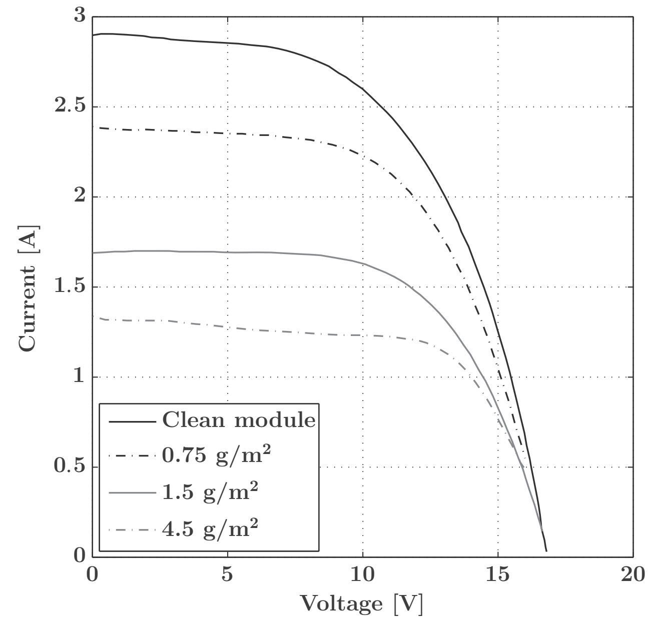

Fig. 11. I–V characteristics of PV module tilted at 30°S with three distinct dust concentration densities exposed outdoors in Kuwait (Al-Hasan and Ghoneim, 2005).

the College of Technological Studies, Kuwait. One of the panels was cleaned regularly, while the other one was made dusty using sand dust particles collected from the nearby desert. Sand dust particles were sprayed using a fan blowing air onto the target PV module so as to apply a nearly uniform dust layer on the cover plate. Fig. 11 shows the I–V characteristics of PV module tilted at 30° at three dust concentration densities. For a dust concentration density of 1.5 g/m^2, the losses in the I_{sc} and maximum output power are approximately 40% and 34%,

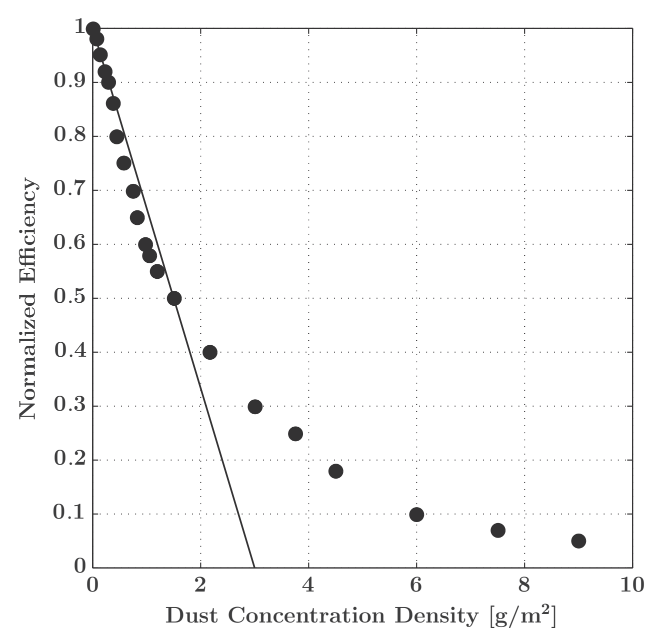

Fig. 12. Normalized efficiency vs. dust concentration density (Al-Hasan and Ghoneim, 2005). Linear approximation is valid up to 1.5 g/m^2. The size of particles is estimated to be 6.4 μm.

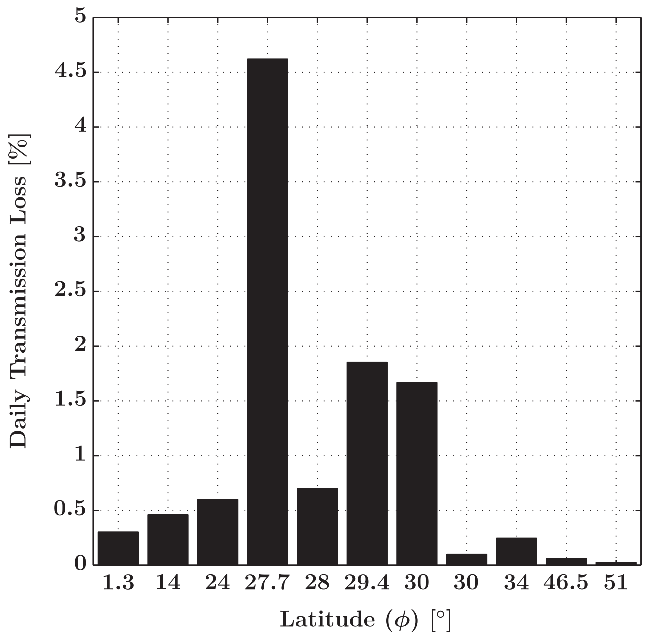

Fig. 13. Maximum daily transmission loss for various latitudes (the *x*-axis is not to scale). The locations in the order of increasing latitude are: Singapore, Singapore (Hee et al., 2012), Bangkok, Thailand (Mastekbayeva and Kumar, 2000), Abu Dhabi, UAE (El-Nashar, 2009), Thar Desert, India (Nahar and Gupta, 1990), Minia, Egypt (Hegazy, 2001), Kuwait, Kuwait (Sayigh et al., 1985), Roorkee, India (Garg, 1974), Helwan, Egypt (Elminir et al., 2006), Pasadena, CA (Hoffman and Maag, 1980b), Morges, Switzerland (Bonvin, 1995), and Leuven, Belgium (Appels et al., 2012).

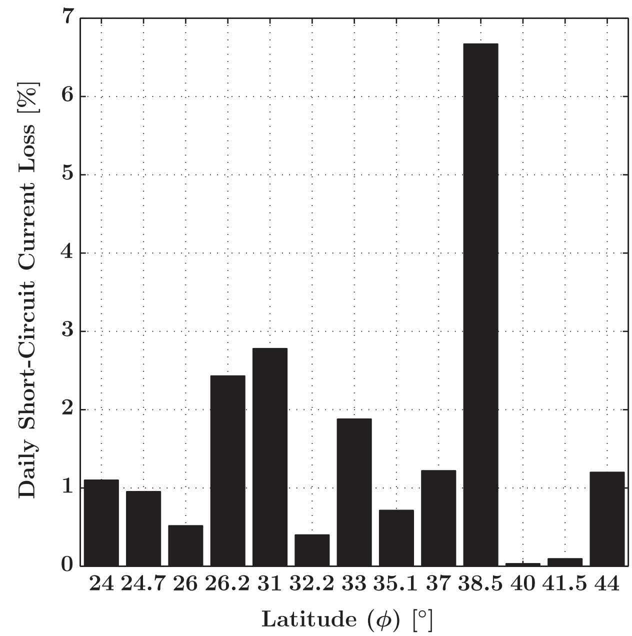

Fig. 15. Maximum daily short-circuit current loss for various locations (the *x*-axis is not to scale). The locations in the order of increasing latitude are: Dhaka, Bangladesh Rahman et al. (2012), Riyadh, Saudi Arabia (El-Shobokshy et al., 1985), Isa Town, Bahrain (Som and Al-Alawi, 1992), Jodhpur, India (Pande, 1992), Arar, Saudi Arabia (Ibrahim, 2011), Colorado Desert, CA (Caron and Littmann, 2013), Mesa, AZ (Cano, 2011), Carrizo Plain, CA (Caron and Littmann, 2013), Southern Central Valley, CA (Caron and Littmann, 2013), Davis, CA (Townsend and Hutchinson, 2000), Berkeley Springs, WV (Maag, 1977), Cleveland, OH (Hoffman and Maag, 1980a), and Eugene, OR (Ryan et al., 1989).

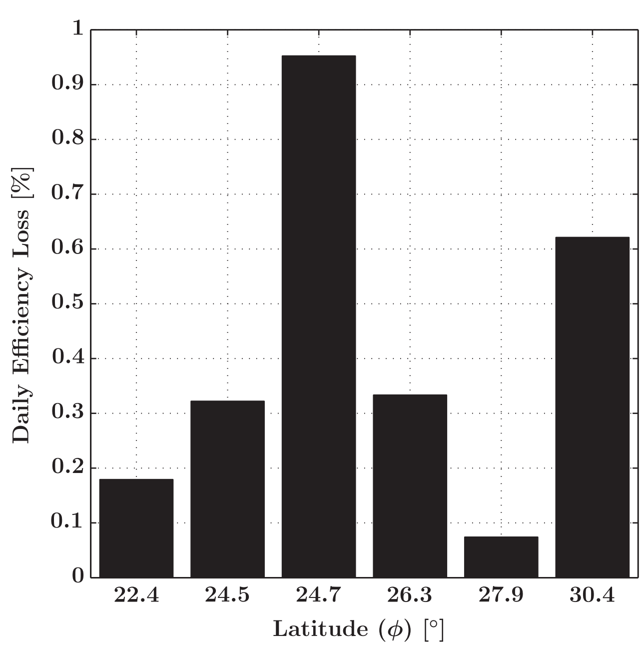

Fig. 14. Maximum daily efficiency loss for various latitudes (the *x*-axis is not to scale). The locations in the order of increasing latitude are: Hong Kong, China (Pang et al., 2006), Abu Dhabi, UAE (Hanai et al., 2011), Riyadh, Saudi Arabia (Salim et al., 1988), Dhahran, Saudi Arabia (Said, 1990), Gran Canaria, Spain (Schill et al., 2011), and Arava Valley, Israel (Boykiw, 2011).

respectively. Fig. 12 also shows the normalized efficiency, defined as the ratio between the efficiency of dusty to clean modules, vs. dust concentration density. The estimated size of sand particles is 6.4 μm. The particle size distributions used by the authors in these experiments corresponded well with measurements of particle size distributions for dust collected from outdoor solar panel. As can be seen in Fig. 12, the rate of normalized drop in efficiency decreases as the dust concentration density increases. Linear approximation is only valid up to 1.5 g/m^2. Similar observation has been reported in previous studies (Al-Hasan, 1998; Hegazy, 2001).

Light transmission reduction as a function of dust concentration density was studied in Boyle et al. (2013), in which some tempered glass plates were exposed outdoors at tilt angles of 0°, 40°, and 180° (facing downward) in Commerce City, CO. The location was chosen to take advantage of dust sources arising from local highway construction as well as a nearby refinery. In order to eliminate the effect of rainfall events, a sheltering rooftop was placed over the glass samples. Variation of the light transmission efficiency vs. dust concentration shows a relationship similar to that reported earlier by Hegazy (2001). Linear approximation of the collected data showed that for dust concentration densities less than 1.5 g/m^2, the transmission reduction was 5.8% per g/m^2.

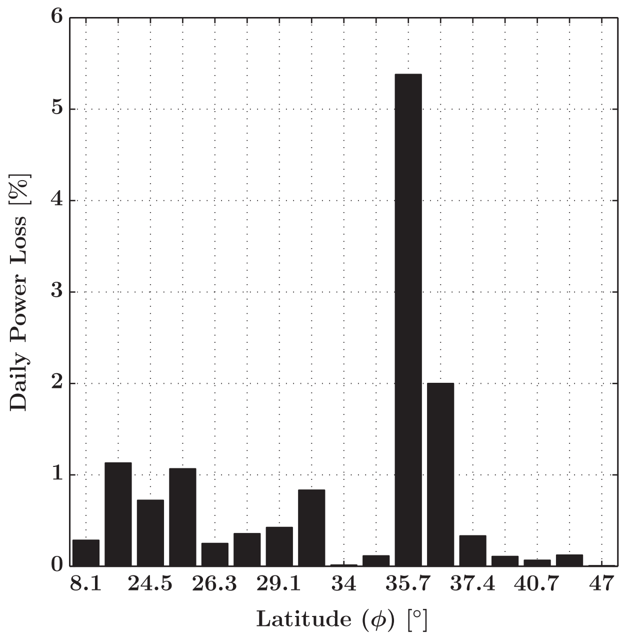

Fig. 16. Maximum daily power loss for various locations (the *x*-axis is not to scale). The locations in the order of increasing latitude are: Ogbomoso, Nigeria (Sanusi, 2012), Dhaka, Bangladesh (Rahman et al., 2012), Abu Dhabi, UAE (Hanai et al., 2011), Riyadh, Saudi Arabia (Salim et al., 1988), Dhahran, Saudi Arabia (Nimmo and Said, 1979), Libya (Mohamed and Hasan, 2012), Hermosillo, Mexico (Cabanillas and Munguia, 2011), Kuwait, Kuwait (AlBusairi and Möller, 2010), Los Angeles, CA (Kimber, 2007), Limassol, Cyprus (Kalogirou et al., 2013), Tehran, Iran (Asl-Soleimani et al., 2001), Malaga, Spain (Zorrilla-Casanova et al., 2013), Mountain View, CA (Lam et al., 2009), Athens, Greece (Kaldellis and Kokala, 2010), New York, NY (Hoffman and Maag, 1980a), Puglia, Italy (Pavan et al., 2011), Bern, Switzerland (Haeberlin and Graf, 1998), and Cologne, Germany (Becker et al., 1997).

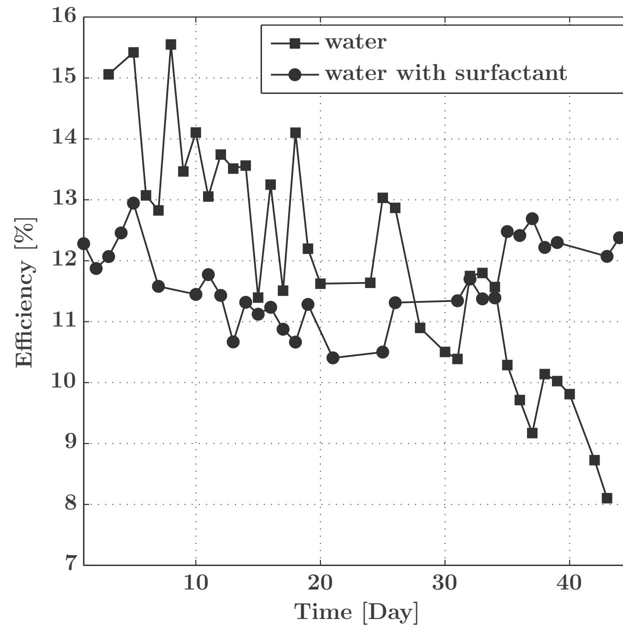

Fig. 17. Efficiency of PV system installed in Cairo, Egypt, after 45 days of cleaning using non-pressurized water without surfactant, and non-pressurized water with surfactant (Moharram et al., 2013). Both cleaning methods were conducted for 10 min daily over a period of 45 consecutive days, albeit at different times of the year.

Figs. 13–16 summarize some of the data presented in Table 2. These data can provide PV system designers with information on the expected loss at each geographical location. Maximum reported daily losses in transmission, efficiency, short-circuit current, and power output are plotted vs. latitude for each region in Figs. 13–16, respectively. In the case of multiple data points for a particular location, only the maximum value has been considered in the plots. Monthly and annual average of solar insolation vs. geographical location is provided in NASA Solar Insolation (2008). Excessive loss of energy-yield is also indicative of local concentration of atmospheric pollutants, as is shown in Fig. 16. Tehran, Iran experiences the maximum daily power loss among the locations studied (Asl-Soleimani et al., 2001). This significant loss is attributable to the severe air pollution of Tehran during the December time frame of the experiment, when Tehran suffers from photochemical smog (Mohammadi et al., 2012). The latter causes transmission loss due to atmospheric particulates. Another example shows significant daily power losses in PV systems are not restricted to installations in desert and arid areas. Specifically, Liqun et al. (2012) report on a two-week exposure of six outdoor PV modules in Taiyuan, China. This city also suffers from severe air pollution and suspended particles in the atmosphere. For PV modules tilted at 45° and 0°, the output power decreased approximately 1.3% and 2.32% per day, respectively, over this the relatively short exposure period.

5.3. Cleaning schedules

The cost of labor and water, particularly where the latter is scarce, as well as loss of energy yield are the primary factors that determine the cleaning schedules required to minimize cleaning cycles while maintaining system performance at an acceptable level. Clearly, the cleaning schedules are dependent on the installation site, local weather, surrounding vegetation, wind pattern and atmospheric dust concentration. For instance, for the flat-plate collectors installed in Riyadh, Saudi Arabia (Sayigh, 1978), cleaning every three days is recommended to obtain satisfactory results. Similarly, a cost/benefit analysis is provided in Pavan et al. (2011) as a guide in choosing a proper cleaning schedule.

To generalize the cleaning schedule, Mani and Pillai (2010) have divided PV installation sites into three climate zones: low-, mid-, and high-latitude regions. For any of these three zones, a cleaning cycle is recommended to improve PV system performance based on the characteristics of PV installation, dust deposition rate, and atmospheric conditions. For example, dry tropical zones in the latitude range 15–25° in northern and southern hemispheres experience rare rainfalls and numerous dust events. Weekly cleaning schedules for PV installations in these areas are recommended as the minimum care needed to maintain consistent average power yield. In low latitude regions, where significant annual precipitation is expected, natural cleaning by rain periodically restores PV cell efficiency.

5.4. Models for predicting energy-yield loss

Although soiling losses depend on many parameters, a number of modeling studies have attempted to predict energy-yield losses for PV installations in different sites. These models are based upon generalized results obtained in different installations in order to simulate losses using predictive software. In order to obtain experimental verification of such a predictive model for PV panels, Kaldellis and Kapsali (2011) deposited red soil, ash, and limestone at various densities on poly-Si PV modules in a laboratory setting, then exposed them to the outdoor environment to collect data on power output vs. dust concentration. The studies show that their theoretical model for energy loss calculation is consistent with experimental results, although various parameters still need to be embedded into the model for more reliable prediction of the energy loss.

Deffenbaugh et al. (1986) improved the predictive capability of existing models of solar industrial process heat (SIPH) systems by introducing a factor that accounts for dust accumulation. The soiling factor was derived from data obtained at six different plants, and it was assumed that the soiling factor rates are the same for the location and collector types studied.

Soiling losses in a test center at Photovoltaics for Utility Systems Applications (PVUSA) in Davis, CA during 1998 and 1999 were analyzed by Townsend and Hutchinson (2000). The results are used in simulation software for studying losses at similar sites. In 1998, a wet El Niño year, monthly soiling losses up to 12% were observed in August 1998, when annual loss was observed to be 4%. In 1999, a year with scant precipitation, monthly losses reached up to 20% in September, and annual losses increased to 7%. Based on these observations, annual soiling losses of 6%, 7%, and 4% were considered for normal, northern California dry, and wet years, respectively.

To generalize the impact of soiling on PV systems, Kimber et al. (2006) studied the performance of sample PV sites in various environments in an attempt to find a soiling pattern. Because natural precipitation was considered as the only cleaning agent in this study, the frequency of rainfall events, particularly the amount of precipitation and its role in increasing the efficiency, were considered as major factors. The authors developed empirical model that include three main components:

(i) site-dependent performance degradation rate,
(ii) minimum amount of rainfall in one day for a full efficiency restoration, and
(iii) number of days that the system is relatively clean since last fully restoration by rain.

The average annual loss prediction varies from 1.5% to 6.2% for eight different PV installation sites in California, Nevada, and Arizona. The model has been validated in Kimber (2007) through evaluation of soiling losses in three identical rooftop PV system installations in the area of Los Angeles, CA.

In a recent study by Caron and Littmann (2013), energy loss due to dust deposition on the First Solar flat-plate PV modules in three different regions in Desert Southwest, California were examined. These three sites include (1) Southern Central Valley, a dry agricultural region, with the maximum loss level of 8.6% recorded in August 2011 attributed to increase of farm activity and fewer rainfall events in the summer months, (2) Carrizo Plain, a dry agricultural region with the maximum loss of 5% in August 2011, and (3) Colorado Desert, an arid region with maximum recorded loss of 2.8% in June 2011. Using the soiling rates in these three monitoring sites, together with the meteorological data, the authors estimated the dust accumulation losses at similar sites in further months.

6. Dust cleaning agents

6.1. Natural cleaning processes

Rainfall is considered to be the most efficient natural cleaning agent for removing contaminant particles from PV surfaces, thereby restoring the performance of the modules. Experiments performed by Appels et al. (2012), Haeberlin and Graf (1998), and Ryan et al. (1989) in the cities of Leuven (latitude: 50.88°N), Belgium, Bern (latitude: 46.9°N), Switzerland, and Eugene (latitude: 44°N), OR, demonstrated the significant restorable effects of sufficient rainfall that makes the regular manual surface cleaning unnecessary. The frequent rainfall in these places is distributed over the year. For solar collectors with sun tracking systems, the position of each collector must be tilted to aid cleaning by rain. In these systems, the stowing position, i.e. face-up to facedown position, also makes a significant difference in the ability of rain to clean particulates. For nearly horizontal positions, light rainfall which includes soluble salt usually leaves undesirable water spots. After a period of exposure time, these dusty spots build up as residues, forming strongly adhering dust layers that cannot be removed without mechanical detergent scrubbing (Bethea et al., 1981). Changing the stowage position of PV panels so as to fully utilize the cleaning effects of rain is feasible only for PV installations equipped with tracking systems. As stated before, dusty rain forms a sticky mud layer that is detrimental to module performance (AlBusairi and Möller, 2010). To restore system efficiency, immediate cleaning after such events is indispensable. This study clearly showed the potentially degrading impact of rain: light rainfall made the performance worse.

The wind also has a dual role in the overall performance of PV cells. Wind carries dust and causes soiling of the

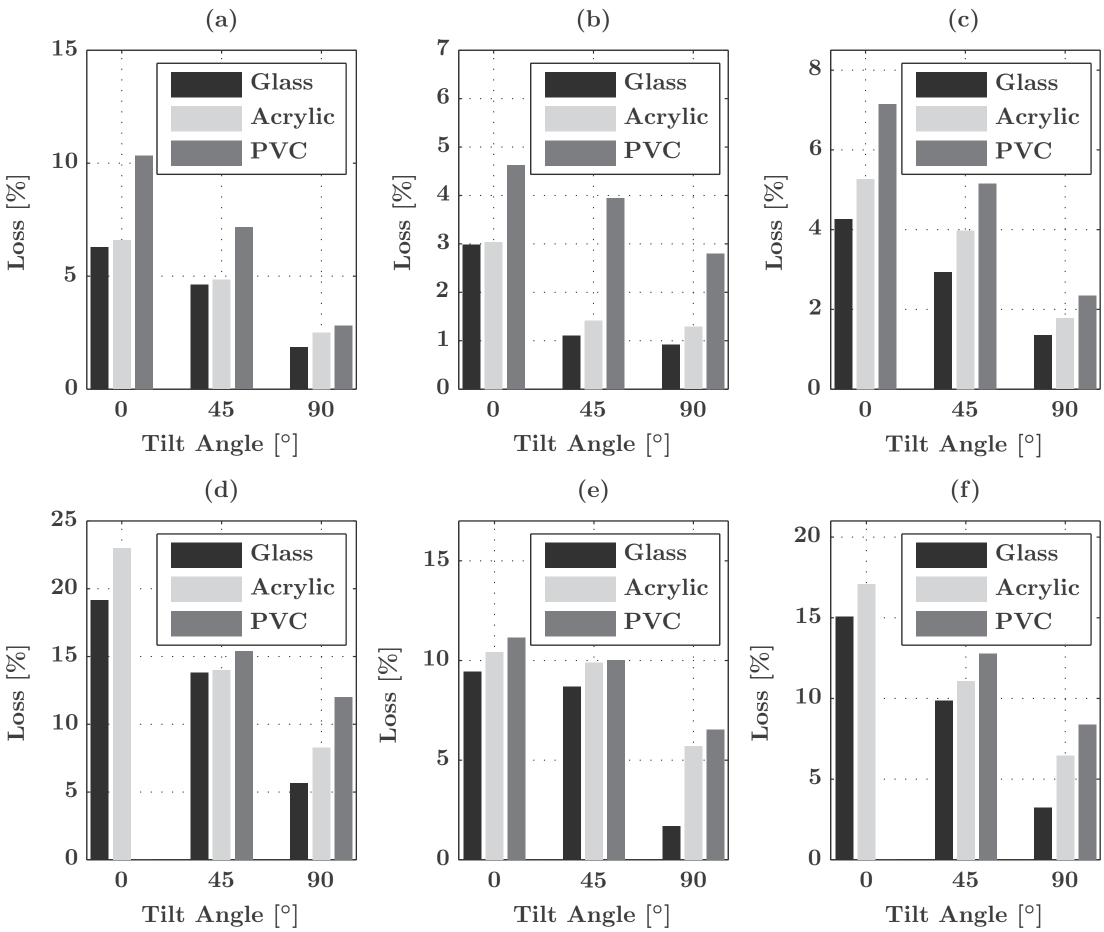

Fig. 18. Light transmission losses for glass, acrylic, and PVC samples tilted at 0°, 45°, and 90°, exposed in Thar desert, India from May 1986 to December 1987 (Nahar and Gupta, 1990): (a) maximum transmission loss for daily cleaned samples recorded in May, (b) minimum transmission loss for daily cleaned samples recorded in January, (c) annual average transmission loss for daily cleaned samples, (d) minimum transmission loss for weekly cleaned samples recorded in April–May period (PVC sample degraded), (e) minimum transmission loss for weekly cleaned samples recorded in January–March period, and (f) annual average transmission loss for weekly cleaned samples (PVC sample degraded) (Nahar and Gupta, 1990).

solar collectors; indeed, it is the primary means of global transport for airborne particles. On the positive side, wind can reduce overall soiling by removing larger dust particles from collector surfaces. In addition, for PV modules made with c-Si solar cells, the cell temperature decreases as the wind velocity increases, thereby improving the efficiency of the system. High wind velocity also reduces the ambient relative humidity, leading to higher cell efficiency (Mekhilef et al., 2012). Higher wind velocity also helps in drying the moisture layer that may form between the dust particles and the surface of the collector, thereby decreasing the adhesion of dust to the surface. As noted by Cuddihy (1980), however, the wind cleaning effect is not very effective for particles smaller than 50 μm, because smaller particles adhere to the surface and resist removal by wind forces, even at air velocities greater than 50 m/s. At 40% relative humidity, wind velocity of 100 m/s removed approximately 10%, 30%, 65%, and 90% of the deposited particles with sizes smaller than 3.5, 10, 25, and 50 μm, respectively (Cuddihy, 1983).

Generally, higher wind velocity will deposit more dust on a PV module surface in a dusty environment. The study by Goossens and Kerschaever (1999) investigated the effects of dust concentration and wind velocity on the performance of a PV cell. In their study, mono-Si PV panels were installed horizontally, parallel to the wind flow direction, inside a wind tunnel. Under outdoor conditions, wind speed generally increases with an increase in installation height. For example, the cleaning effect of wind is more prominent for PV panels installed at a relatively higher level above the ground (Cano, 2011). In addition, wind direction relative to the azimuth angle of the solar collector plays an important role in dust settlement and distribution. As discussed by Goossens et al. (1993), wind direction and collector position have been shown to have even more crucial impacts, compared to the effects of wind velocity on collector performance in wind tunnel simulations and subsequent field experiments in the Negev desert, Israel.

6.2. Manual cleaning with water

Cleaning with tap (or distilled) water, often mixed with detergent, followed by wiping with a soft cloth is the most common practice for cleaning PV panels in small-scale

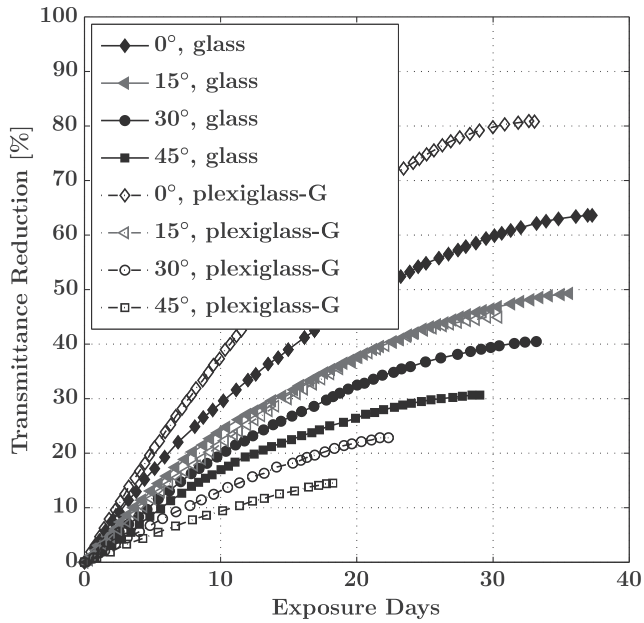

Fig. 19. Transmittance reduction for glass and plexiglass-G specimens exposed outdoors in Kuwait (Sayigh et al., 1985).

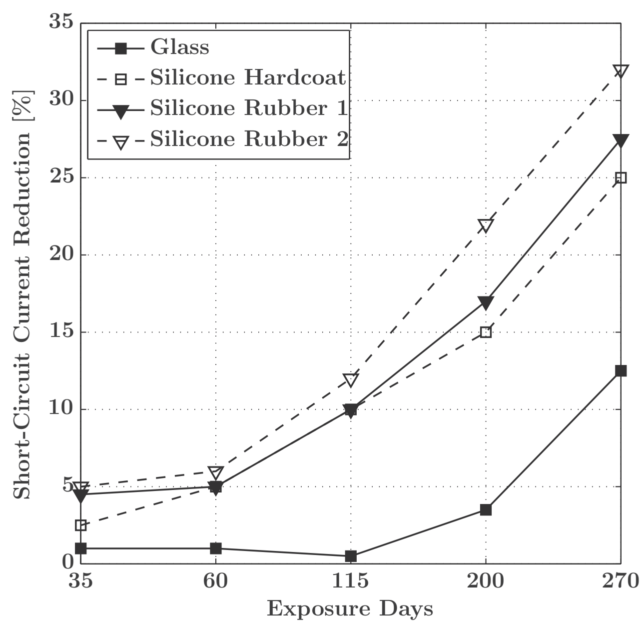

Fig. 20. Reduction in I_{sc} for four different glazing materials exposed outdoors in Pasadena, CA (Hoffman and Maag, 1980b). Note the x axis is not to the scale.

installations (Mohamed and Hasan, 2012; Zorrilla-Casanova et al., 2013; Becker et al., 1997). For large-scale PV plants, however, high-pressure water jets, followed by brushing, has been reported in many investigations (El-Nashar, 1994, 2003; Pavan et al., 2011; Kimber, 2007). It is considered one of the most effective cleaning methods among the existing practices, because it is less harmful to the collector surface, is economical, and has minimal environmental impact.

The effectiveness of brushing after washing has been clearly demonstrated by Pavan et al. (2011). In their study, panels in two large-scale (1 MW_p) plants in Puglia, Italy were cleaned using high-pressure distilled water, but panels in one plant were also brushed after washing. Data acquisition performed before and after cleaning events during 2010 showed that the cleaning procedure increased output power of the plant followed by brushing to 6.9% as opposed to only 1.1%, without brushing. The primary reason for this relative efficiency increase is that highly adhered fine particles were removed only with brushing. Notwithstanding the improving effect of brushing, excessive surface scrubbing will eventually degrade the performance of the system by scratching the glazed surface of the PV panels. Such surface degradation could be more detrimental for mirror surfaces in concentrated solar collectors (Freese, 1979). The authors concluded that scrubbing must proceed as a delicate process that must be performed with extreme care.

The earliest works reporting cleaning of PV modules with detergents go back to the late 1970s and early 1980s (Hoffman and Maag, 1980b), during which cleaning methods in three different centers were reported: (1) NASA Lewis research center wherein Alconox–Tide solution was used with a scrub cloth, followed by rinsing with tap water and drying, (2) MIT/Lincoln Laboratory where Alconox solution was applied with a sponge, rinsed with tap water, and dried by a squeegee, and (3) Jet Propulsion Laboratory where a water-based degreaser was applied with a sponge and rinsed with tap water. These methods of water cleaning were found to be effective.

One recent work studying surfactants was published by Abd-Elhady et al. (2011). These studies were conducted in a laboratory environment using three types of surfactants: anionic (Sodium docecyl Sulphate), cationic (Cetylpyridinium Bromide), and zwitterionic (Tween-80). Surfactants anionic, cationic, and zwitterionic have hydrophilic heads of negatively charged, positively charged, and two oppositely charged groups, respectively. Surfactant is sprayed through a nozzle on dusty samples, and the results are analyzed using light microscopy images. The authors concluded that anionic, followed by zwitterionic, and then cationic were the most influential surfactants for removing deposited sand particles. This order was reversed for carbon particles deposited on the glass surfaces. To get the best surface cleaning results, a mixture of anionic and cationic is recommended. This recommendation has been utilized in studies by Moharram et al. (2013), in which the concentration of each surfactant was 1 g/l of sprayed water, and the mass ratio of the anionic to cationic components was 1:1. More details of the cleaning system used in Moharram et al. (2013) are provided in Section 6.3. Fig. 17 compares the efficiency of PV systems subjected to two cleaning methods: (i) non-pressurized water without surfactant and (ii) non-pressurized water with surfactant. The efficacy of cleaning using water with surfactant is almost constant, while it decreases as a function of cleaning cycles

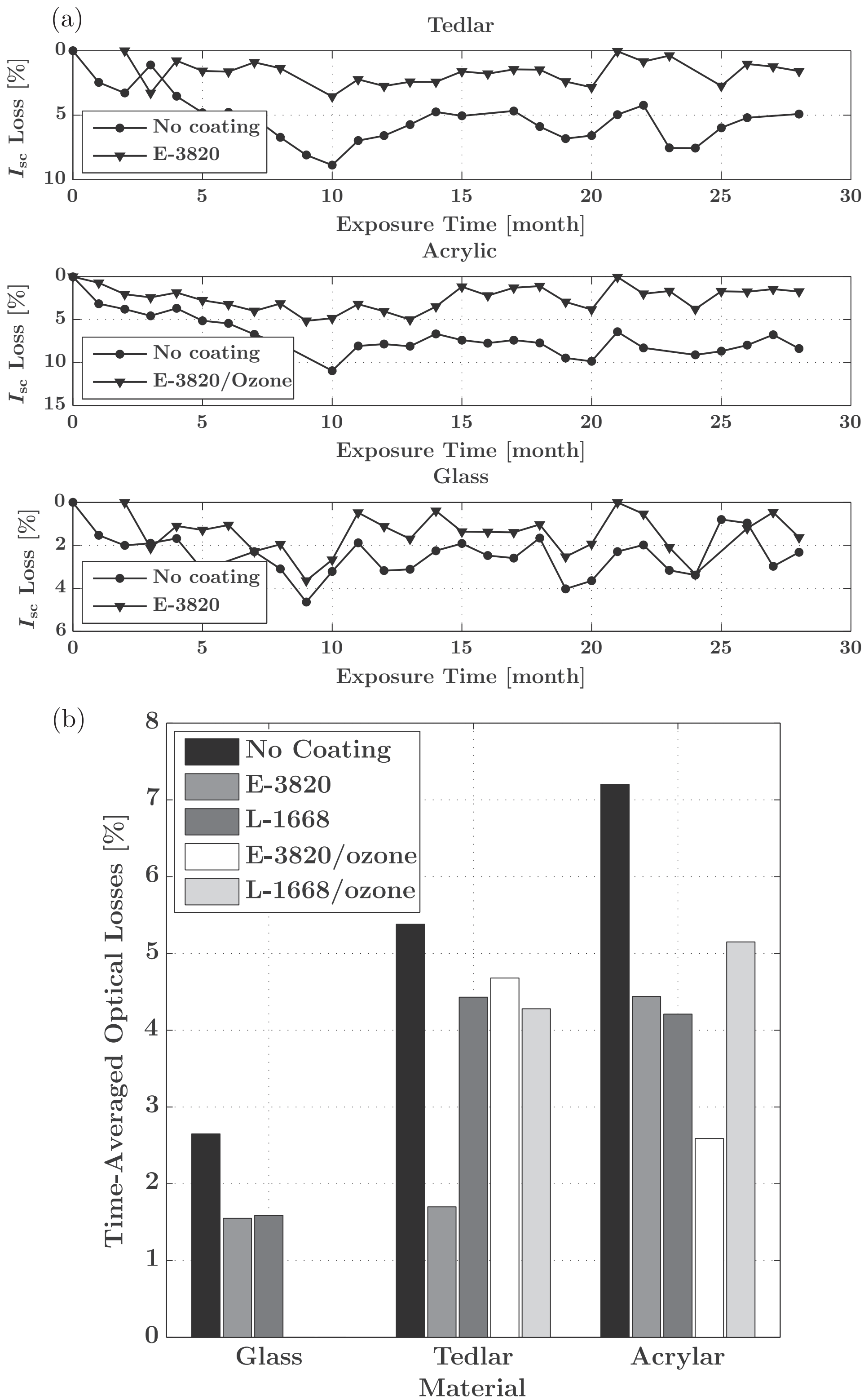

Fig. 21. Soiling data of PV modules with different cover materials and coatings (Cuddihy et al., 1986).

when no surfactant is used. A linear approximation shows that daily efficiency reduction is almost 0.14% for surfaces cleaned with only water. The discrepancy in the initial efficiency of the PV system in Fig. 17 is attributed to the deteriorating effect of higher temperatures during the second 45-day period of cleaning using surfactant.

The effectiveness of surfactants on different types of soiling over the entire particle size distribution was considered by Abd-Elhady et al. (2011). In large-scale field studies, however, these detailed methods with controlled composition of cleaning solutions are most probably unattainable. Effects of detergents, their chemical properties, and potential side effects on the surfaces over long time periods are comprehensively discussed by Miller and Kurtz (2011).

6.3. Automated cleaning systems

The cleaning procedure consists of labor, water resources, and cleaning solutions, in which both labor and water comprise the major fraction of the cost of cleaning. Numerous attempts using computer-controlled mechanical devices have been made to automate the procedure in order to minimize water usage and maintain PV module efficiency at an acceptable level.

In order to maximize the energy output of a PV module, an integrated single axis sun tracking system equipped with a cleaning mechanism was designed and tested, as reported in Tejwani and Solanki (2010). The azimuthal angle tracking system, comprising a microcontroller, stepper motor, and gear box, starts its rotation from an initial perpendicular-to-ground position at 6 AM, and completes its 360° rotation in 24 h using steps of 15°, maintaining its normal angle to sun radiation during the day. The PV module surface becomes perpendicular to the ground twice a day. At these times, a brush fitted on a sliding rod cleans the system, rotates, then follows an upward-downward path due to gravity. Hence, the PV module is brushed twice a day in this configuration. The efficacy of the design was corroborated by comparing daily energy output, whereby the tracking module with cleaning equipment showed a 15% increase compared to that of a module equipped only with a tracking system.

To maintain the proper functionality of stand-alone PV systems installed on offshore wellhead towers in United Arab Emirates, two automated techniques: Programmable Logic Controller (PLC) and microcontroller-based mechanisms have been tested to keep birds away from PV arrays (Lamont and Chaar, 2011). Since the main performance-limiting factor in such wellhead-tower installations is due to bird droppings, using abrasive cleaning methods, i.e. wiping/brushing the soiled surface, seems indispensable. Both of these systems share the same mechanical movement pattern to clean the surface. In PLC based systems, desalinated seawater is used for maintaining the tilted surface wetness when the wiper moves. The microcontroller-based cleaning system has been equipped with a water tank to spray the surface before the cleaning wiper initiates the three complete cycles.

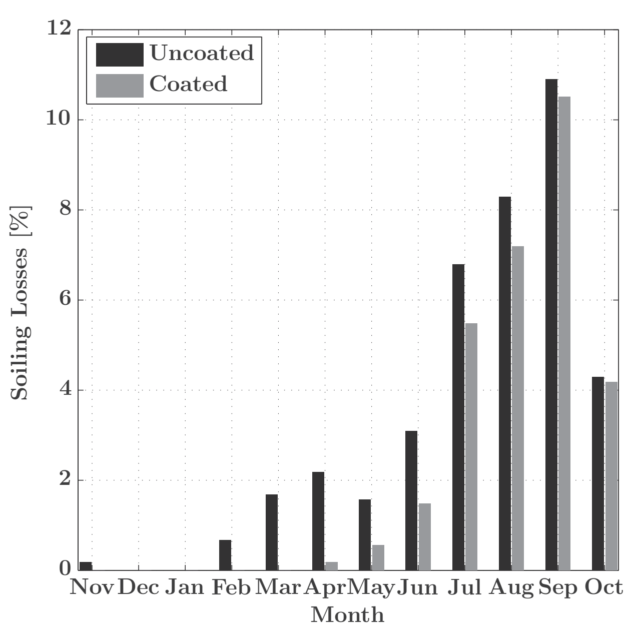

Fig. 22. Monthly soiling losses for coated and uncoated poly-Si PV modules (Piliougine et al., 2013).

One automatic cleaning method was developed by SolarWash (2008), whereby nozzles are placed along the top of the PV arrays. Upon activation, these nozzles spray cleaning solution when commanded by a microprocessor. Although satisfactory results have been achieved for small-scale PV installations, this method still faces some challenges. Scalability for large PV plants, significant amounts of water and consequent water evaporation at high ambient temperatures, and the non-uniformity of flowing water on the lower sections of the array modules are some of technical challenges of this method.

Moharram et al. (2013) have followed a similar approach as discussed in SolarWash (2008). They installed water nozzles at the top of mono-Si PV modules exposed outdoors in German University in Cairo (GUC), Egypt. These nozzles sprayed water on the panels.In oder to recycle water, they collected water in an underground tank using a drainpipe at the bottom of the PV panels. Since collected water carries accumulated dirt from PV panels, the suction pipe for intake is placed at the center of the tank so that the sediments are not returned to the intake water for cleaning. The water can be recycled and partially filtered by gravitational sedimentation within the storage tank. Water cleaning also reduced the temperature of the solar cell: increasing V_{oc}. Using this water cleaning process, it was possible to restore PV system efficiency significantly after soiling. Based upon an approximate 10% loss in initial water loading over the 45 days period of operation, the daily water consumption for cleaning 1 m^2 of PV panels was approximately 0.047 l. Water consumption increases to 15.89 l/m^2 without the water recycling system.

Similar to the window cleaning robot made by RobuGlass (Kochan, 2005), Anderson et al. (2009), developed PVCleaner Robot, a PV surface cleaning robot. It consisted of two moving trolleys attached to the top and bottom of the panel and one cleaning head moving upward and downward while brushing the surface. Cables connecting the cleaning head to the trolleys provide movement for brush rotation while guiding the cleaning head to follow a "square-wave" cleaning pattern. During the initial tests, a cleaning rate of 2.33 m^2/min using 0.58 l/m^2 was recorded. Since a water-restoring mechanism was employed in surface brushing, efficiency in water usage was improved approximately 100 times compared to water spraying method.

Robotic cleaning reduces water consumption but increases installation and maintenance costs. This point has been clearly shown by Ju and Fu (2011). In their study, two identical monocrystalline PV systems were exposed to the outdoors in Shenzhen, China. One of the PV systems was equipped with a motorized, mechanical cleaning system comprised an electrical motor and a brush with water spray, while the other was left unattended to be cleaned by natural precipitation. The PV system equipped with cleaning system yielded more output power, compared to the naturally-cleaned PV system. However, operating cost of the cleaning system including water and energy consumed by the motors, was found to be higher over the same test period.

6.4. Effect of cover-plate materials and surface treatment

The passive cleaning methods consist of using a surface modification of transparent cover plates either by decreasing adhesion of dust particles or by improving wettability (surface energy) of the front surface for efficient water cleaning.

6.4.1. Cover-plate materials

The most common cover plate, low-iron glass, has proved its durability and ability to protect surfaces against damaging effects, such as hail, over long time periods. In one of the earliest works on this topic, performed by Garg (1974) in Roorkee, India, he observed that plastic cover plates accumulate more dust relative to glass plates due to their electrostatic characteristics. Furthermore, for long exposure periods, the transparency of the plastic films degrades due to ultraviolet radiation, changing their color and increasing opacity. To study the effect of cover plates on solar panel installations in Riyadh, Saudi Arabia, three identical cells of glass, Perspex (or acrylic), and no cover were examined (Sayigh et al., 1979). It was noted that plastic covers were not stabilized against UV radiation, and eventually their color changed from transparent to yellow. Additionally, long-term exposure of plastic covers to excessive heat made them brittle.

Nahar and Gupta (1990) investigated the affects of soiling on the transmissivity of glass, acrylic, and polyvinylchloride (PVC) glazing materials. Fig. 18 shows the transmission reduction for samples tilted at 0°, 45°, and 90° subject to different cleaning schedules. Experimental data, shown in Fig. 18, indicate that PVC is the most inferior cover plate compared to acrylic and glass materials for the same tilt angle and cleaning cycle. For example, the maximum and minimum transmission losses of PVC samples tilted at 90°, cleaned weekly, show approximately 2 and 4 times more, respectively, compared to glass samples oriented vertically over the same time period and cleaning cycle. In addition, it was noted that horizontally tilted PVC samples degraded after 305 days of exposure, because they were unstable under ultraviolet radiation (Figs. 18(d,f)).

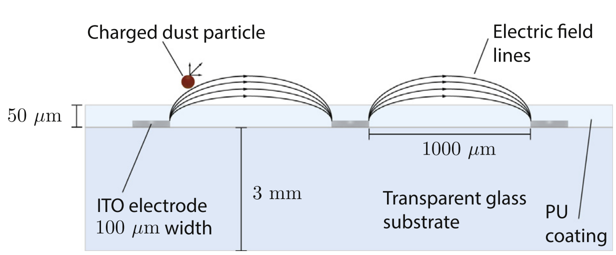

Fig. 23. The cross section of the Electrodynamic Screen (EDS) (Mazumder et al., 2011).

Along similar lines, Sayigh et al. (1985) exposed several 4-mm thick window glass and 2-mm thick plexiglass (acrylic) samples to the outdoors in Kuwait, and transmission loss was tested. Glass samples tilted at 0°, 15°, and 30° exhibited transmission losses of 64%, 48%, and 38% in 38, 35, and 33 days, respectively, while transmittance reductions in Plexiglas specimens tilted at 0°, 15°, and 30° were found to be 80%, 46%, and 22% after 36, 31, and 23 days, respectively. Fig. 19 shows the behavior of glass and Plexiglas samples during exposure in Kuwait.

The impact of dust on the short-circuit current I_{sc} of PV modules using four different glazing materials: glass, silicone hardcoat, and two silicone rubbers, were studied by Hoffman and Maag (1980b) in Pasadena, CA. Losses in I_{sc} of PV modules with the aforementioned materials as covering layers over a 270-day exposure period are shown in Fig. 20. After 270 days of exposure, the losses in I_{sc} were 12.5% and 32% for PV modules with glass and silicone rubber as front surfaces, respectively. As the rainy season started in the next cycle (not depicted in Fig. 20), the short-circuit current of the PV module with a glass cover was fully restored.

6.4.2. Surface treatment (coating)

The performance of low-soiling coatings tested as seven different locations across the US over a 28-month study period is provided comprehensively by Cuddihy et al. (1986). Reduction in I_{sc} was measured to quantify the performance degradation of the cover materials. The candidates for the surfaces were low-iron glass, Tedlar fluorocarbon film (Du Pont Co., 100BG3OUT), and a biaxially oriented acrylic film Acrylar (3 M Corp., X-22417). To examine the effect of coating, two fluorocarbon coatings were considered:

(i) L-1668: an experimental fluorochemical silane produced by 3 M Corp.
(ii) E-3820–103B: an experimental coating of perfluorooctanoic acid chemically reacted with a Dow Corning silane, Z-6020.

Fig. 21(a) shows the reduction in I_{sc} for the Tedlar, Acrylic, and glass samples with and without a fluorocarbon anti-soiling coating E-3820. Short-circuit current losses were as high as 10% and 12% for uncoated Tedlar and Acrylic samples, respectively, while uncoated glass samples

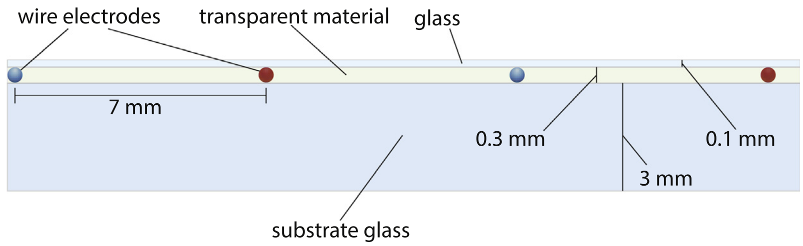

Fig. 24. The cross section of the cleaning system used for dust removal from solar panels (Kawamoto and Shibata, 2013). An inclination angle, not illustrated here, is used in the setup.

experienced losses up to 5%. Using an E-3820 coating yielded maximum losses in I_{sc} of 3.5%, 5%, and 3.8% for coated Tedlar, Acrylic, and glass samples, respectively. The soiling data averaged over the 28-month study period are provided in Fig. 21(b). The glass, Tedlar, and Acrylar control (no coating) samples had optical losses of 2.65%, 5.38%, and 7.20%, respectively while coated samples with E-3820 showed 41.5%, 68.4%, and 38.33% improvement compared to uncoated ones. Therefore, the glass sample outperforms Tedlar and Acrylic samples, and coating with E-3820 further improves its performance.

Bonvin (1995) used five different glass types, viz., Solite, Optiwhite, Optiwhite covered with Tefzel®, Optiwhite with hydrophobic coating Glasscad®, and Optiwhite with a special coating called Clear Shield to study the effects of dirt on loss of transparency for flat-plate PV panels installed near the railway station of Morges, Switzerland. Among tested glass materials, the Optiwhite glass showed the best resistance to dirt deposition.

Among the recent outdoor studies, Cabanillas and Munguia (2011) observed that dust deposition decreased the maximum power of a-Si, mono-Si, and poly-Si PV modules by 14%, 8.5%, and 5.2%, respectively, after outdoor exposure in Hermosillo, Sonora, Mexico, for 20 days. The front cover of the a-Si PV module was plastic, while mono-Si and poly-Si PV modules were equipped with glass covers. The significant maximum power decrease in a-Si:H photovoltaic module is attributable to its plastic cover, which attracts and holds dust particles more than does glass due to the force of electrostatic attraction.

Similar outdoor experiments were conducted to evaluate the performance of different coating materials, specifically mono-Si and a-Si cells covered with white glass, and poly-Si with an epoxy cover. These samples were tested in a laboratory environment using a test chamber and sun simulator (Jiang et al., 2011). The dust deposited on the poly-Si cell covered with epoxy was more than the other cell types with glass surfaces.

In addition to cover material, coating can influence the dust deposition rate significantly for tilted surfaces. Appels et al. (2012) performed an experiment in which coated glass samples were tilted at 35° and exposed for three weeks to the outdoor environment in the city of Leuven, Belgium. The purpose of the tests was to examine the effects of coating on transmission loss. For glass samples with anti-reflection (AR), self cleaning (SC), and multilayer (ML) coatings, the transmittance reductions were found to be 1.75%, 1.30%, and 0.85%, respectively, while the uncoated glass sample showed 2.63% transmission loss. Although thorough performance evaluation of these coatings will require much more exposure time, the glass sample with multilayer (ML) coating showed better performance over three weeks of exposure.

In Singapore, TiO_2 was coated on two sample glass slides in two different thicknesses of 40 nm and 60 nm to study optical transmission losses (Hee et al., 2012). Initial transmission of uncoated glass slide, and coated slides with 40 and 60 nm TiO_2 coating were measured as 90.86%, 90.15%, and 89.15%, respectively, while their optical transmission decreased at the rate of 0.261%, 0.231%, and 0.167%, per day after 10 days of exposure. Better transmission loss rate of coated glass slides is attributable to the self-cleaning effect of the TiO_2 coating which helps rain to remove deposited dust particle more effectively from do glass slides. Notwithstanding the fact that the sample with a 60 nm coating showed slightly less initial transmission compared to uncoated and coated glass with 40 nm coating, the rate of transmission loss is smaller and will hopefully continue, indicating superior performance over longer exposure periods.

For photovoltaic modules exposed to outdoors in Arizona, 5% efficiency improvement was observed in modules treated with a hydrophilic anti-soiling coating (Brown et al., 2012).

Piliougine et al. (2013) evaluated the effect of anti-reflective and anti-soiling coatings on polycrystalline PV modules exposed outdoors for one year at the University of Málaga, Spain. The coating material, a product of the Asahi Kasei Corporation, is a composition of metal-oxide nanoparticles and a binder of hybrid polymer. Six poly-Si PV modules of the same type and manufacturer, divided into two groups, three with coating and three without, were selected for the experiment. From the start of the experiment in November 2010 until May 2011, the short-circuit current losses for both coated and uncoated PV modules were less than 3% due to the restorative effect of natural precipitation, while losses monotonically increased in the summer months when the area experienced no rainfall at all. Transmission losses during summer months increased to 10% for coated and 12% for uncoated PV modules.

Table 3
The advantages and disadvantages of different cleaning agents/methods for dust removal from PV module surfaces.

Cleaning method/agent	Advantages	Disadvantages
Natural cleaning: Rainfall, melting snow, wind, and gravitational forces	• Heavy rainfall and melting snow can fully restore the efficiency of the solar panel • Tracking systems can be used for increasing cleaning efficiency of rain • There is no cleaning cost • High wind can remove larger dust particles from collector surfaces	• Light rainfall in dusty atmosphere followed by dusty wind greatly increase dust deposition and reduce efficiency • Rainfall events in arid- and semi-arid zones are infrequent • In semi-arid and desert lands occasional rain does not provide a reliable cleaning method
Cleaning with high-pressure water jet	• Cleaning can be performed whenever required • High PV module efficiency can be maintained routinely	• It has significant cost for labor and water resources; and requires trained personnel • Water resources are very limited in arid zones • Efficient cleaning of PV modules requires demineralized or distilled water • Deposition of organic salts creates a film over the glass surface requiring scrub cleaning with brush. The process requires highly trained personnel to avoid scratches • Scrub cleaning requires surfactants, which may be harmful to environment
Controlled water spray	• It can be activated by using a pump automatically or manually • Well-designed cleaning process may conserve water • Except regular maintenance the labor cost is minimized • Water cleaning process, when used, reduces cell operating temperature and increases efficiency	• It needs water resources and surfactant (if removal of organic film is needed) • It is not convenient for large-scale PV systems • Scalability of the method is not cost-effective • Spraying process does not provide uniform cleaning over the entire surface • It has loss of water by evaporation
Robotic cleaning system	• Efficient water usage systems have been utilized for economical cleaning • Both cleaning and scrubbing processes can be automated	• It needs water resources/surfactant for cleaning • It is still in developmental stages and scalability of the method in large solar plants is not established • It needs a team of technicians for supervision of robot operation • Power consumption of the robotic device is not cost effective in some applications • It has high operation and maintenance costs
Anti-soiling coating	• It improves cleaning efficiency of natural cleaning agents • It lasts for couple of years • It is an effective method for making the module surface either highly hydrophobic or hydrophilic	• Their lifetime is limited and is greatly site-specific • Re-application of coating might reduce the optical performance • Dust adhesion is greatly dependent upon the electrostatic characteristics of the film and dust
Electrodynamic screen	• It does not need water resources or labor for operation • There is no mechanical movement involved in cleaning procedure • The process involves application of removal forces applied directly on the dust particles • The cleaning process can be activated automatically or manually depending on the need • The power consumption is very low	• The technology is in developmental stages • Performance is limited to RH less than 50% • Durability of this technology has not been established yet

Fig. 22 shows the soiling losses for the coated and uncoated PV modules during the study period. As can be seen in Fig. 22, in August and September, when the rate of dust accumulation is highest and rainfall is lowest, both coated and uncoated modules show significant soiling losses, whereas the difference is more prominent in June and July months. During the one-year exposure period, coated PV modules showed average daily soiling losses of 2.5%, while uncoated modules an a daily average of 3.3%.

If textured glass is used as a front surface for PV modules, their performance will increase due to a decrease in reflection losses (Nositschka et al., 2007). In the experimental PV facilities at the University of Málaga, Spain, Piliougine et al. (2008) compared the dust accumulation rate of two different textured glass surfaces, with non-textured glass as the front cover of monocrystalline PV modules. The south-facing modules were inclined at 30°. After one year of exposure, no significant difference in soiling losses was observed between textured glass and non-textured glass surfaces.

6.5. Emerging cleaning methods

Automated cleaning processes, particularly those that do not require water, are most desirable for maintaining the high efficiency of solar plants in dusty environments. Most of the processes applied to date use complex mechanical and motorized mechanisms, which are not yet well established as scalable, economical, or reliable. It is often difficult or impractical to have a team of technicians available for maintaining operation of the cleaning robots, particularly at stand-alone installations in remote areas. Large-scale cleaning operations with water followed by scrubbing require large amounts of water annually, the use of specially designed vehicles, and an experienced operations team. Such methods are expensive and difficult to implement when fresh water is in short supply. In many large-scale solar plants, cleaning must performed using desalinated seawater, leading to added energy load.

The cost of water and labor has the potential to be a significantly prohibitive factor, as has been highlighted by Ju and Fu (2011). The arid nature of site's location exacerbates the use of water resources, which may needed for other vital functions in the surrounding community. An analysis by Sheratte (1979) shows that labor represents about 45.7% of the total cleaning cost at a CSP plant at the Naval Weapons Center (NWC) in China Lake, CA. A high-pressure spray method is used at this facility.

One alternative approach for cleaning using electrostatic forces for dust removal is currently being studied. The fundamental principle of the so-called electrodynamic screens (EDS) was introduced in 1970s at the University of Tokyo by Masuda et al. (1972) and Masuda and Matsumoto (1973) that showed that a traveling wave of electric field could convey charged aerosol particles in a traverse direction. The method has since been improved and advocated by researchers for removing dust from solar panels in future space exploration missions (Calle et al., 2009; Atten et al., 2009; Sharma et al., 2009; Mazumder et al., 2006). An EDS consists of a series of alternating electrodes embedded in a transparent dielectric film and applied to the surface of the solar collector. The dust removal process requires no water or moving parts, and it can be implemented as frequently as needed without interrupting the operation of the plant.

Transparent electrodes can be deposited on the glass cover plates of PV modules or on the front surface of the solar mirrors. The dielectric film coats and protects the electrodes from environmental degradation. The electrodes are activated by three-phased, low frequency voltages of about 1-kV magnitude. The activated electrodes produce an electric field on the surface of the dielectric film that varies with time and space. This non-uniform electric field exerts Coulomb and dielectrophoretic forces on the any particles residing on the surface. The dust particles become charged and are levitated by the Coulomb force. The traveling wave transports the particles laterally across the surface and off the solar collector. The process restores the function of the now clean collector.

Depending upon the activation method, single-phase or multi-phase, standing-waves or traveling-waves, respectively, can be generated to repel and convey particles. The electric field varies with respect to both time and space, thus providing both lift and transport forces that move away the dust particles.

The dust removal efficiency for an EDS clearing Mars simulant dust has been shown to be more than 80% using three-phase electrode activation (Mazumder et al., 2006). Significantly, the power required to energize the EDS electrodes is only about 10 W/m^2 for each panel during activation time. Moreover, constant activation is not needed. Just a few minutes each day can be sufficient. Given that the power generated by the typical solar panels is about 800 W/m^2 during maximum solar insolation hours, the power needed by the EDS a negligible fraction of the power produced by the solar panel itself.

Although the EDS was developed initially for removing dust in space exploration applications, recent studies are emerging that aim to adopt the EDS for dust removal from solar panels installed on Earth. Different parameters adversely affect EDS operation in solar plants, including small particle size, adverse chemical composition, and high relative humidity. The latter is not a significant issue in space exploration, but it is a major factor in terrestrial applications of EDS technology.

In fabrication and experimental performance evaluations of EDS, Mazumder et al. (2011, 2013) deposited line electrodes 50–100 μm in width on a glass substrate, followed by a thin coating of dielectric material such as polyurethane (PU) or Ethylene Tetrafluoroethylene (ETFE). Three-phase voltages between 700 and 1000 V_{p-p} in magnitude were then applied to charge deposited dust particles and remove them from the solar-panel surface. Fig. 23 shows a schematic view of the EDS in operation. Dust removal efficiency of more than 90% was achieved for an EDS activation time of less than a 2 min, restoring more than 98% of the original power.

In a recent study by Kawamoto and Shibata (2013), wire electrodes were embedded in the cover glass plate of a solar panel and activated through a single-phase voltage source. The electrodes were first placed on a 3-mm thick glass substrate, then covered with a 0.1-mm thick glass plate to prevent insulation breakdown. Because single-phase voltage pulses were used, dust particles were not transported laterally, but rather repelled from the surface. The glass plates were inclined, hence the gravitational force helped to remove particles once they were levitated from the surface. Fig. 24 shows a cross section of the design. The system was shown to be capable of removing more than 80% of dust particles in the range 50–300 μm, but it was not effective outside of this range. Poor performance for small particles was attributed to the fact that Coulomb and dielectrophoretic forces are weaker than electrostatic image and adhesion forces. For larger particles outside the range, the gravitational forces are much stronger and can impede the removal particles.

Particle removal mechanisms in a standing-wave electric curtain were investigated both numerically and experimentally by Sun et al. (2012). In these studies, it was shown that a fraction of particles could potentially accumulate on the edges of the electrodes, consequently affecting the performance of the electric curtain. Liu and Marshall (2010b) used the method of discrete-element modeling (DEM) to investigate the effects on electric curtain performance of particle–particle interactions and also adhesion of particles to the dielectric surface. Because the electric curtain is powered using the solar panel, a control strategy is established in Qian et al. (2012) to determine optimal operation of an electric curtain for maximum overall energy yield. Analysis of the particle trajectories under the influence of different forces using a simulation program was performed by Horenstein et al. (2013). Experimental data on correlation between theoretical trajectory calculations and observed particle motion via video recording are included. Characterization of particle transport by standing waves in an electric curtain is also provided in Liu and Marshall (2010a), in which constant migration of the particles and a hopping behavior similar to Brownian motion along the surface are identified.

As a method for removing deposited dust from cells used in Mars exploration rovers, Williams et al. (2007) have conducted experiments using mechanical vibration to restore the power of photovoltaic cells. They attached piezo-ceramic actuators in the back of a 1 m 0.6 m rectangularly shaped solar-panel mock-up. The test panel was placed horizontally in a controlled environmental chamber, and Mars dust simulant was deposited on its surface. A 30-V_{p-p} sinusoidal wave with 60-V_{dc} offset was then applied to the piezoceramic actuator at different resonant frequencies up to 5 kHz. Based on the frequency response function, efficient dust removal was observed at higher frequencies, particularly above 2 kHz.

Table 3 summarizes the advantages and disadvantages associated with each cleaning method mentioned above.

7. Conclusion

Soiling of the optical surfaces causes both energy-yield loss and permanent degradation of the surface properties, thereby affecting light transmission and reflection. These adverse effects are functions of both the physical and chemical properties of the dust found in a given geographical location, the surface properties of the collector, and the climate, particularly RH, temperature, wind velocity, and frequency of dust episodes. Detailed investigations on the development of efficient and economical methods of dust mitigation for enhancing the surface properties of the solar collectors for maintaining high optical efficiency is needed. One of the objectives of this review has been to provide solar energy engineers with information on the natural soiling losses in different parts of the world and to likewise provide insight into the environmental degradation and needed mitigation for maintaining high efficiency.

The impact of dust deposition on several photovoltaic and photo-thermal systems reported in the literature over the last four decades has been briefly reviewed. The key findings are as follows:

In designing solar plants, it is common to consider loss factors at every stage, from the incident solar irradiance to the load connection, either by using grids or isolated single or distributed loads. This review shows that soiling related energy-yield loss and cleaning costs must also be considered at any given solar plant location. Dust accumulation on the collectors surface will depend on the rate of deposition and the rates of dust removal via wind.

Attenuation of the solar radiation reaching the cells or the receiver depends upon the dust mass concentration on the surface (g/m^2), the size distribution of the dust, and their chemical compositions. Radiation intensity is reduced by both absorption and scattering by the accumulated particles. Particles with high absorption coefficients, such as soot and iron oxides (0.2–2.0 μm in diameter), absorb incoming radiation, and fine particles with their size comparable to the wavelength of light will scatter light more efficiently than others. Finer particles also have large specific surface area. Thus fine particles deposited on the collector cause more energy loss compared with the same mass concentration of large particle deposition.

The anticipated amount of loss can be estimated from the geographical location, atmospheric dust concentration, prevailing wind velocity, RH variations, and precipitation rates. In the case of flat-panel PV modules, the higher the tilt angle, the lower is the rate of dust deposition. Cleaning of dust by wind and rain also greatly improves as tilt angle increases.

Large-scale solar plants are installed in semi-arid and desert areas where dust storms are common and rainfall is rare. Dust storms cause major loss of the performance of PV installations. These storms are mostly unpredictable, except that they occur more frequently in certain months of the year. As such, appropriate strategies are needed to alleviate the problem. Solar collectors equipped with tracking systems can reduce the negative effect of such dust episodes if they are stowed in appropriate positions to minimize the effect of dust storms. Such strategies are also helpful during wind storms for protecting the support structures used for the collectors.

Cleaning with water using effective detergents is the most commonly used method for cleaning. Use of a water recycling mechanism improves the efficiency of the entire cleaning system. The efficacy of the cleaning using surfactants depends upon the type of dust composition and the adhesion of dust to cover plate materials. Frequency of cleaning is critical, as the adhesion of dust increases with the residence time of the dust on the collectors before each cleaning. In the regions where RH is very high, during the early morning period with possible dew formation, the adhesion of dust having soluble organic and inorganic salts creates a cement-like formation on the glass surface, which requires subsequent scrubbing. Light rain in dusty weather leaves the collector surface spotty with a sticky dust layer that drastically degrades performance. Immediate cleaning after such events is recommended to restore systems efficiency.

Glass is the most durable cover plate material for stability against thermal and photochemical degradations and impact resistance. It is also the most desirable surface for water based cleaning using high-pressure water and scrubbing. By using the appropriate coating, the performance of glass can be further improved, although cost is still a prohibitive factor in commercial, large-scale operation. With growing concern over water resources, particularly in arid areas, any cleaning method that use less water for cleaning solar collectors can be both cost effective and environmentally safe. Emerging automatic cleaning methods, particularly using electrodynamic screens, are promising alternatives for cleaning solar collectors with minimum operational cost. These processes are still under development for commercial applications.

Acknowledgement

We acknowledge the Grant from the Department of Energy (DOE CSP DE-EE0005794) for supporting a research project on prototype development and evaluation of self-cleaning concentrated solar power collectors.

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