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Soiling of photovoltaic modules- Review

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Abstract. The atmosphere is contaminated with certain minute particles of size 500µm. The deposition of these dust particles over the panel surfaces is referred as Soiling of Photovoltaic (PV) panels. The particulate matters originating from agricultural activity as well as construction works, air pollution, pollen, bird droppings and growth of lichens are the main sources of soiling on the PV panels. It is influenced by location-based meteorological conditions like rainfall, wind speed, and humidity, tilt angle, the sources of soiling, and the texture of cover glasses. The soiling is one among the major losses in the PV performance. Owing to this reason, the PV panels should be cleaned at regular intervals. There are manual and self- cleaning methods. The cleaning by manpower is most common. The self-cleaning comprises of active as well as passive cleaning techniques. This paper reviews about different methodologies used to study the soiling of PV modules and the different factors affecting soiling.

1. Introduction

Nowadays, the solar energy is the fastest growing renewable energy in residential, commercial, agricultural, and industrial applications. The photovoltaic (PV) system converts the solar power obtained from the sun to electricity through the semiconductor materials like silicon and cadmium telluride. The solar energy is abundant, clean and infinite energy[2]. The main advantage of solar energy is that it provides green energy with no carbon emission. But the solar energy is intermittent and varying depending on the environmental and climatic conditions. Besides these, there are many other factors affecting the PV performances like the photovoltaic technology used, tilt angle, array mismatch, distribution losses, inverter efficiency, soiling of PV panels, etc.

The deposition of dust and other minute particles over the PV modules is termed as Soiling[1]. It is one of the major loss factors affecting the PV performance. The soiling loss is the power loss resulting from the dust, snow, dirt, and other particles that covers the PV module surface. The various sources of soiling are pollution, bird droppings, the growth of lichens, particulate matter arises due to the wind, agricultural activities, construction works, pedestrian and vehicular movements[3].

Section II describes the different factors affecting the soiling of PV panels. In section III, the various methodologies used in soiling study at different locations are given in detail. Section IV describes the

tilt angle optimization and PV potential assessment. Section V describes the cleaning aspects of PV panels.

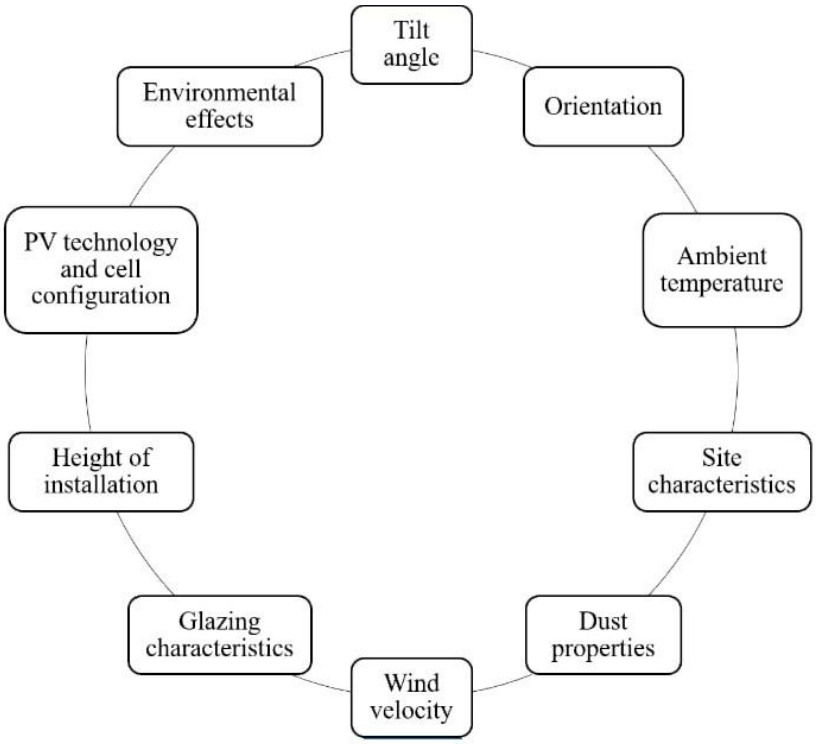

Figure 1. Factors affecting soiling of PV panels [4][5][6].

2. Factors affecting soiling

The soiling is a phenomenon influenced by location-based meteorological factors and climatic conditions, tilt angle, the sources [1]. Soiling may lead to partial shading of cells as the surface is covered with dust and thereby optical losses may occur. The different factors affecting soiling of PV panels is given in figure 1. It includes PV installation factors and environmental factors. The installation factors that affect soiling are height of installation, tilt angle, orientation, glazing characteristics, and PV technology used. The different environmental factors are wind speed, dust properties, ambient temperature, rainfall, humidity, and vegetation.

2.1. Tilt angle and orientation

The dust particles may settle more on horizontal surfaces than the tilted surfaces [7]. The larger dust particles will roll down from top to bottom of a tilted PV module. Hence, the effect of gravitational force in dust accumulation increases as the tilt angle increases. The PV modules that are facing towards the wind will get the more influence in dust deposition compared to the PV modules kept far away from the direction of the wind. Hence, the orientation of PV panels is an important factor influencing the cleaning of panels by wind movement.

2.2. Ambient temperature, Pressure and humidity

Dust, humidity, and wind are the factors depending on the sun's radiation and the environment. At high ambient temperature and low relative humidity, wind carries the dust easily. The water vapour will condense and form water drops at low temperature [3]. High RH increases the dirt adhesion and forms a sticky surface over the solar panels [8].This led to adhesive panel surface which attracts more particles from surroundings. When the airspeed is higher and there is low pressure, less soil accumulation occurs and vice-versa. The humidity changes with the irradiance in a non-linear manner

and irradiance itself causes little variations in open circuit voltage and causes large variations in short-circuit current [3].

2.3. Site characteristics

The site characteristics involve the characteristic features of the location for PV panel installation. The area can be a metropolitan city or a village. The vegetation, natural habitats, pollution rate, pedestrian and vehicular traffic varies with location. Based on these variations, the soiling of solar panels vary as the dust pollutant types differ with geographic location.

2.4. Dust properties

The different properties of dust include chemical, biological, electro-static and physical properties. The dust deposition will be different for different dust properties. The physical properties of dust includes its size, shape, and weight. The small dust particles settle down more than that of the larger dust particles on the PV panel surface [2]. The different electrostatic property includes neutral, positively charged and negatively charged particles. Generally, the charged particles cause more dust deposition than the neutral particles because the like charges attract and unlike charges repels.

2.5. Wind velocity

There are two effects of wind speeds on the dust settlement. In [5], it is claiming that the high wind velocities result in high soiling rate than the low wind speeds. But in other papers, the high wind velocity will clean the panels against soiling if it is oriented towards the wind movement. It is seen that the chances of dust settlement are more at light wind speeds. For the wind with high amount of airborne dust, the possibility of dust accumulation is more [3].

2.6. Glazing characteristics

The dust accumulation on PV panels varies with the property of panel surface. The surface texture and additional coating on the PV panels comprise the surface property. For plane surfaces, the dust accumulation is lesser. The textured panels have rough and irregular surfaces increase the soiling on panel surface [2]. A protective layer of glass on the PV module surface is less affected by dust deposition.

2.7. Environmental effects

The environmental effects on soiling arise from the variations in atmospheric and climatic conditions. The air borne dust concentration, probability of dust storm, the occurrence of dew, rainfall, volcanic eruptions, etc. contribute to soiling of PV panels.

2.8. PV technology and cell configuration

The soiling affects the different PV technologies differently based on the spectral transmittance. The PV technologies include monocrystalline PV panels and polycrystalline PV panels. The performance of PV panels varies with its technology.

3. Methodologies for soiling study

The methodology of soiling studies comprises of natural and artificial soiling. The natural soiling study is done by keeping the PV panels exposed to sun for a certain period of time and allows the soiling of panels from the surrounding dust particles. In artificial soiling, the dust particles are artificially prepared and spread on the panels using the technologies like spray gun. In both the cases, the effect of soiling on the electrical parameters (voltage, current, Fill Factor, efficiency, etc.) and optical parameters (transmittance, reflectance, etc.) of solar panels are studied and analysed.

3.1. Natural Soiling

The natural soiling of PV panels is the dust accumulation over solar panels when it is exposed to sun. The main sources of natural soiling are the dust particles present in the atmosphere due to air pollution, bird droppings, agriculture, construction works, pedestrian and vehicular movements. The effect of soiling on PV performance is studied through natural soiling by measuring the electrical and optical parameters of the PV panels.

3.1.1 Measurement of electrical parameter. In Garcia [1], a long-term soiling study of about 30 years was conducted in a moderate sub-tropical climatic region in Italy. They installed 28 silicon PV panels in 1985 and pull apart in 2014 without cleaning. They used manual cleaning and high-pressure water sprayer for cleaning the soiled panels. The figure 2 shows the I-V characteristics of PV panels before and after cleaning. It is observed that the power output increased after the cleaning of the PV panels.

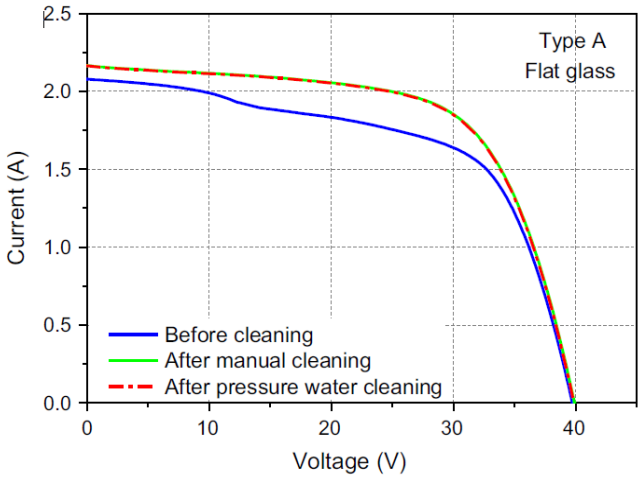

Figure 2. I-V characteristics of the PV panel [1].

Another study conducted by Jose Cano et. al [9], the influence of tilt angle on dust deposition over the panels is investigated. As the short circuit current is proportional to the sun's radiation reaching the solar panels, the measurement of I_{sc} can analyse the effect of tilt angle on soiling loss. The experimental setup for the study is given in figure 3. The figure 4 inferred that the soiling losses decreases with increase in the tilt angle of solar panels.

Figure 3. Experimental set-up for studying the effect of tilt angle on soiling [9].

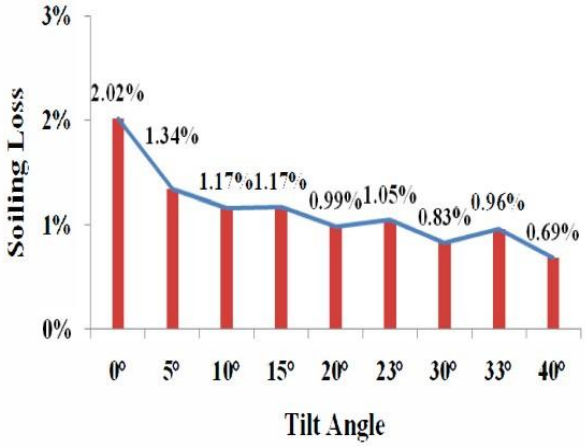

Figure 4. Plot between average soiling loss and tilt angle [9].

The setup consists of 18 PV modules which are calibrated. The modules are divided into two groups of nine PV panels, tilted at nine different angles. One group of panels are cleaned periodically and others kept uncleansed. They calculated the soiling loss at different tilt angle by measuring the daily insolation received by cleaned panels (DI_{cm}) and uncleansed panels (DI_{sm}). The soiling loss is calculated from equation (1).

$$\text{Soiling loss (\%)} = [(DI_{cm}-DI_{sm}) / DIcm] \times 100 \quad (1)$$

King et. al [10] done an improved work of [9] where the experimental setup is named as soiling stations. The soiling stations monitor the soiling losses by comparing the PV output of soiled PV panels to the PV output of cleaned panels [12]. A soiling station is shown in figure 5. The modified experimental setup consists of modules with two half cells at different tilt angles. In each half cells, one sensor was kept clean and others are uncleansed throughout the study. The Data Acquisition System (DAS) collects the Isc values and other required data at an interval of one minute. The soiling stations were installed in five different locations in the USA.

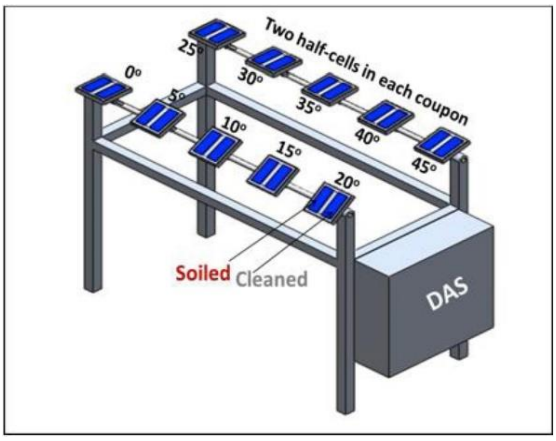

Figure 5. Pictorial representation of a Soiling station [10].

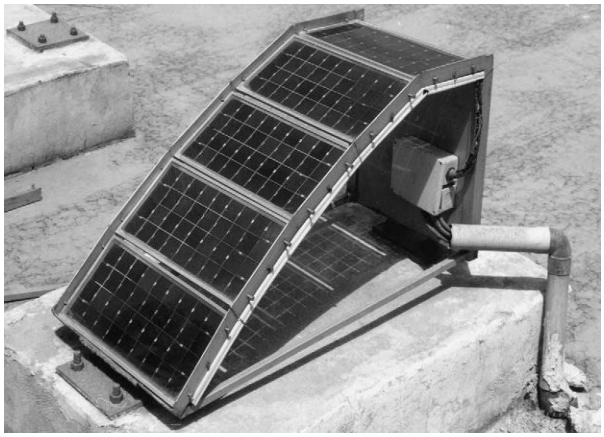

Figure 6. Experimental set-up for studying the effect of tilt angle and air pollution [11].

The air pollution is tremendously increasing in big cities. In order to study the effect of air pollution and tilt angle on solar panel performance, an experimental study was done in Iran [11]. The figure 6 shows the experimental setup in which the panels are tilted at 0°, 23°, 29°, 35°, 42°. The PV output energy is measured in the first month of every season. The results shows that the panels tilted at 29° produced more energy and owing to the effect of pollution, the output reduced up to 60%.

In another study, the effect of tilt angle on soiling is studied in [13] by using the mini-modules (replica of commercially available PV modules) at different tilt angles. The data of voltage, current are measured using multimeters at regular intervals of time. The results reveal that the cleaning of panels is greatly influenced by the rain event and wind speed depending on the tilt angles.

In Micheli et. al [14], the soiling stations were installed in 20 different locations in the USA. A time series data of these locations during a year is plotted with soiling ratio and rainfall against the month of the year. The soiling ratio is the ratio of short circuit current of soiled panels to the short-circuit current of the cleaned solar panels.

In [15], the effect of different PV technologies on electrical parameters is studied. Three different types of PV panels is used in the study. The PV panels are amorphous silicon, monocrystalline silicon and polycrystalline silicon panels. The parameters like irradiation, electrical energy output, and accumulated dust are measured during a period of five months. A mathematical model is developed by

relating the dust accumulated over the PV panels and reduced electrical output of PV panels. The dust accumulated is measured using Dust-fall jar methods from Pollution Control Department.

3.1.2 Measurement of optical parameters. The optical parameters like transmittance of cover glasses used in solar panels is an important factor while considering the PV performance since the irradiation from the sun has to pass through the cover glass before it is converted into electricity.

In Gholami [16], a different methodology with a time period of 70 days was adopted for finding the factors affecting dust settlement and its influence in transmittance of the cover glasses. The figure 7 shows the experimental arrangements. The surface density of dust is calculated from the ratio of the weight of dust accumulated to the glass surface area. The amount of dust accumulated is the difference between the mass of glass samples before and after the experiment. The effect of wind direction is taken into account while doing the experiment. The wind swept away the dust deposited over the glass panels facing towards the wind. This will reduce the surface density of dust. In the paper, a correlation equation between transmission coefficient and surface density of dust is specified but there is no evidence for this equation.

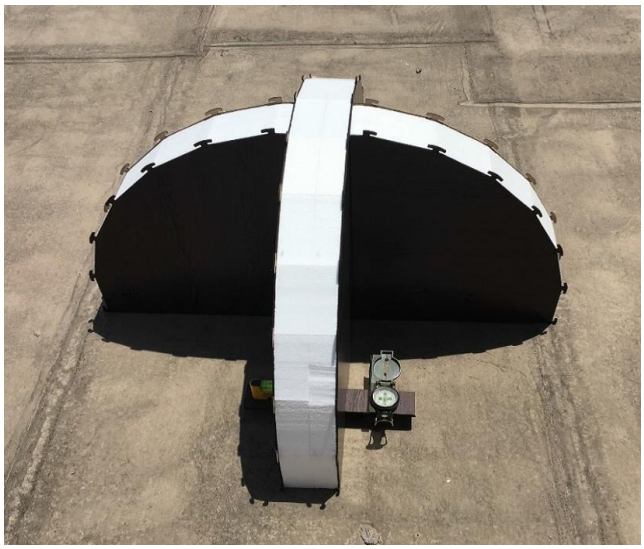

Figure 7. Arrangement of glasses for finding the factors affecting dust settlement [16].

A study conducted in Belgium[17] analyses how the transmittance get affected the PV performances. For that, they have done the experiments for natural as well as artificial dust accumulation over the PV modules. In the experiment for natural soiling, the normal glass samples are installed as two sets (one is shielded from rain and other is unshielded from rain) which are tilted at different angles. It is observed that the transmittance is reduced for the panels shielded from the rainfall. The physical properties of dust and its cleaning aspects were also studied show that demineralized water reduces the transmittance loss percentage. The study infer that the transmittance increases with increase in tilt angles.

Elminir et. al [18] conducted a similar study to analyse the reduction in transmittance due to soiling. The experimental setup consists of 100 glass plates installed at different tilt angles in different orientations. They also studied the reduction in power output in monocrystalline solar cells. The experimental study shows that at smaller tilt angles, larger will be the reduction in transmittance. The effect of angle of incidence on soiling is studied with five different PV technologies like monocrystalline silicon, polycrystalline silicon, a-Si, CdTe, CIGs technologies [19]. They have compared the angle of incidence effect with soiling density and found that the angle of incidence effect is inversely proportional to the soiling density. A similar study is conducted in different

locations in John [20]. They compared the dust deposition on a-Si, monocrystalline, multicrystalline, and CIGs modules in a hot and dry climate by measuring the spectral reflectance and quantum efficiency.

A natural soiling study done in Kuwait [21] studies the property of dust accumulated over the PV panels and the reduction in transmittance in detail. The dust samples were collected during one month in 2010 and 2011. The composition of materials contained in the collected dust was determined using X-ray diffraction (XRD) analysis. The spectrometer arrangement is used to find the transmittance of each sample. The study reveals that the dust accumulation adversely affects the regions with lesser wavelength.

3.2. Artificial Soiling

The artificial soiling of PV panels is done to analyse the effect of soiling on the electrical and optical parameters of PV panels. The dust samples will be prepared in the laboratory and applied over the PV panels in a confined environment. The artificial soiling study is a fast process when compared with natural soiling.

3.2.1 Measurement of electrical parameters. In 1993, El. Shobokshy and F. Hussein [22] done the artificial soiling on PV cells. The dusting is done in the laboratory from the artificially created dust. The standard deviation and mean size of dust particles were verified. They studied the I-V characteristics of the cells in every tests. The deposition density of dust over the cell surface is calculated and its effect on the different electrical parameters like voltage, current, Fill Factor (FF) were also verified. The result says that the parameters are greatly affected by dust settlement and observed a reduction of 84% in power output for 250 g/m^2 dust deposition.

The natural soiling and its evaluation is a time consuming and expensive process. The soiling loss estimation is affected by the site-specific factors like soil type, geographical location, and the climatic conditions [23]. A work done in India gives a solution for this problem. The methodology involves the dust collection from six interested locations inside the country and the soiling is done in the laboratory. A soil suspension is prepared and deposited over a borosilicate solar glass substrate using spray gun technology. The difference in weight of soiled and clean glass substrate gives a parameter called Soil Gravimetric Density (SGD). The constituents of dust particles is determined by XRD elemental analysis of dust. The quantum efficiency loss, short-circuit current density and spectral transmittance were calculated. The study showed that the soiling loss increases with the SGD. The study concluded with the comparison of dust samples collected from different locations.

While many type of research and studies concentrated on the influence of dust on PV performances, Z Ahmed et. al [24] find the effect of various dust pollutant types on the electrical parameters like voltage, current, Fill Factor (FF), etc. The soiling experiment is conducted in a laboratory and dust density is calculated. The electrical parameters are compared with dust density for various dust types. The I_{sc} and power output has the same effect on dust accumulation. But the change in the open circuit voltage is not affected by deposition of dust till the dust particles block the light completely.

3.2.2 Measurement of optical parameter. Burton and King [25][26] have done the artificial soiling experiment in a laboratory. The Arizona dust, a soot mixture, a mixture of Arizona dust and soot mixture were the dust types used in the experimental study. The dust is prepared and sprayed to a glass substrate using a spray gun. The quantum efficiency and transmission of light through the samples is measured using UV/vis spectroscopy. The UV/vis spectroscopy shows that the soot mixture blocks more amount of light to fall on the substrate than Arizona dust. In a work done by S Boppana [27], the dust is prepared and sprayed using a spray gun with laser pointer. They measured the quantum efficiency, soiling density, and reflectance of the polycrystalline and monocrystalline silicon mini-modules and the results are obtained by comparing the measurements between the two PV technologies. The paper claims that the reflectance loss can be used a measure of soiling density.

Appels [17] also done an artificial soiling experiment using white sand, clay, and cement and measured the transmittance using a spectrometer. They found a relation between the dust accumulation and power output by conducting artificial dust deposition on two types of PV panels exposed to the atmosphere. The results show that the decrease in power output and the decrease in transmittance of glass is approximately equal.

Kathy Brown et. al [28] analyses the PV performance in the desert regions considering the soiling and humidity. Normally, desert regions are characterized by high temperature and low Relative Humidity (RH). A laboratory experiment for the dust deposition on different glass samples is done and its reflectance is measured. The paper compares the optical performance of glass samples covered with hydrophilic anti-soiling coatings to that of uncoated samples.

4. Tilt angle optimization and PV potential assessment

The tilt angle should be such that to obtain maximum output from the PV panels. The tilt angle can be fixed or solar trackers. The solar tracker is expensive. So fixed tilt angle is very common. It is proven that the maximum PV output in a particular location is obtained when the fixed tilt angle is equal to the latitude angle of that location. The PV potential depends on the various environmental factors and weather conditions. So a location-based study is relevant for the maximization of PV potential. The tilt angle optimization is a methodology adopted for enhancing the PV potential.

In [29], tilt angle optimization and potential assessment are done by considering the solar radiation data of Aligarh city. The monthly average of daily solar radiation is estimated. From that optimization of the tilt angle is carried out by Liu Jordan model. The paper [30] says that there are various types of potentials namely, theoretical, technical, economic and implementation. For the land occupation of the PV generator, some terms such as Packing Factor (PF), spacing factor, performance ratio, ground cover ratio and occupation factor and inter-array spacing. The inter-array spacing between the solar panels is an important factor to avoid the shading effect. The ratio of the total area of PV array to the actual area of land occupied by all the PV array is known as packing factor. In [30], the photovoltaic energy potential and power potential is derived by considering the packing factor. This ensures the maximum of land area utilization for PV installation with maximization of PV potential.

5. Cleaning aspects of PV panels

The PV modules should be cleaned frequently for obtaining maximum PV performance. The manual cleaning and self-cleaning are the two methods of panel cleaning. The manual cleaning is found to be more efficient for better PV performances [1]. The cleaning by manpower is the conventional and effective manual cleaning method. Through manual cleaning, the effective removal of hard soiling sources like bird droppings is possible [5]. The problems with manual cleaning are high labour cost, abrasive damage of panels with improper handling [31]. Also, manual cleaning is not suitable for PV installations at large heights and off-shores. There are active and passive methods of cleaning the PV panels.

The PV panels should be kept at optimum tilt angles to obtain not only the best performance but also to get the cleaning effect by rainfall. Heavy precipitation will keep the PV panels clean. However, the light rain will wash away the dust partially and dust will be deposited on the bottom side of the PV panels. It is found that a small rainfall (less than 1mm) is enough for the reduction of soiling losses and continue to increase immediately after the rain [9]. The water cleaning through high-pressure water sprayer, mechanical cleaning by using wipers, use of electrodynamic screens and hydrophilic or hydrophobic surfaces are the other methods for mitigation of dirt settlement. The active methods of self-cleaning include cleaning with water, mechanical cleaning, and electrodynamic coatings. Some of the passive methods of self-cleaning are natural cleaning by rain, super hydrophobic and hydrophilic surfaces on the PV panels. The robots for cleaning of PV panels against soiling are advanced methods which are under research. The cleaning with robots are advantageous because of its features like fast response, low power consumption, stable operation, and more reliable than other cleaning techniques [5].

6. Conclusion

Dust causes severe performance degradation of PV modules. Both the environmental factors and installation factors contribute to the soiling of PV panels. It blocks the solar irradiation falling on solar panels, reduces the transmittance of cover glasses, and introduces a partial shading effect on the PV panels. The paper discusses the different methodologies adopted for soiling study. The soiling can be analysed from natural and artificial soiling. In natural soiling, the PV panels are directly exposed to sunlight and allowed to soiling from the surrounding dust particles. The artificial soiling is carried out in laboratories with dust particles prepared artificially. The studies analyse the effect of electrical parameters (voltage, current, Fill Factor), optical parameters (transmittance, soiling density), and other environmental factors like tilt angle, wind speed, rainfall, humidity on soiling. The cleaning of solar panels are expensive and different techniques for cleaning are emerging day by day to enhance the PV performance.

7. Future work

A future work on the optimization of tilt angle of the panels to maximize the PV potential by reducing the effect of soiling will be done. The enhancement of self-cleaning capability of panels against soiling will be analysed.

References

[1] J. Lopez-garcia, A. Pozza, and T. Sample, “Long-term soiling of silicon PV modules in a moderate subtropical climate,” Sol. Energy, vol. 130, pp. 174–183, 2016.

[2] F. Mohd, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, “Dust as an unalterable deteriorative factor affecting PV panel â€TM s ef fi ciency : Why and how,” Renew. Sustain. Energy Rev., vol. 65, pp. 1267–1278, 2016.

[3] S. Mekhilef, R. Saidur, and M. Kamalisarvestani, “Effect of dust , humidity and air velocity on efficiency of photovoltaic cells,” Renew. Sustain. Energy Rev., vol. 16, no. 5, pp. 2920–2925, 2012.

[4] M. Mani and R. Pillai, “Impact of dust on solar photovoltaic (PV) performance : Research status , challenges and recommendations,” Renew. Sustain. Energy Rev., vol. 14, no. 9, pp. 3124–3131, 2010.

[5] W. Juzaili, H. Abdul, S. Shaari, and Z. Salam, “Performance degradation of photovoltaic power system : Review on mitigation methods,” Renew. Sustain. Energy Rev., vol. 67, pp. 876–891, 2017.

[6] J. J. John, “Characterization of Soiling Loss on Photovoltaic Modules , and Development of a Novel Cleaning System,” p. 146, 2015.

[7] M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, “Power loss due to soiling on solar panel: A review,” Renew. Sustain. Energy Rev., vol. 59, pp. 1307–1316, 2016.

[8] A. Sayyah, M. N. Horenstein, and M. K. Mazumder, “Energy yield loss caused by dust deposition on photovoltaic panels,” Sol. Energy, vol. 107, pp. 576–604, 2014.

[9] J. Cano, J. J. John, S. Tatapudi, and G. Tamizhmani, “Effect of tilt angle on soiling of photovoltaic modules,” 2014 IEEE 40th Photovolt. Spec. Conf. PVSC 2014, pp. 3174–3176, 2014.

[10] B. King, G. Tamizhmani, S. Tatapudi, V. Rajasekar, and S. Boppana, “Regional soiling stations for PV: Design, calibration and installation,” 2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015, pp. 1–4, 2015.

[11] S. Farhangi and M. S. Zabihi, “The effect of tilt angle , air pollution on performance of photovoltaic systems in Tehran,” vol. 24, pp. 459–468, 2001.

[12] M. Gostein and B. Stueve, “Accurately Measuring PV Soiling Losses Using Module Power Measurements,” pp. 2–4, 2013.

[13] M. A. Afridi et al., “Determining the Effect of Soiling and Dirt Particles at Various Tilt

Angles of Photovoltaic Modules To cite this version :," 2017.
[14] L. Micheli, D. Ruth, M. G. Deceglie, M. Muller, D. Ruth, and M. G. Deceglie, "Time Series Analysis of Photovoltaic Soiling Station Data : Time Series Analysis of Photovoltaic Soiling Station Data : Leonardo Micheli," no. September, 2017.
[15] N. Ketjoy and M. Konyu, "Study of Dust Effect on Photovoltaic Module for Photovoltaic Power Plant," Energy Procedia, vol. 52, pp. 431–437, 2014.
[16] A. Gholami, A. Saboonchi, and A. A. Alemrajabi, "Experimental study of factors affecting dust accumulation and their effects on the transmission coefficient of glass for solar applications," Renew. Energy, vol. 112, pp. 466–473, 2017.
[17] R. Appels, B. Lefevre, B. Herteleer, and H. Goverde, "Effect of soiling on photovoltaic modules," Sol. Energy, vol. 96, pp. 283–291, 2013.
[18] H. K. Elminir, A. E. Ghitas, R. H. Hamid, F. El-hussainy, M. M. Beheary, and K. M. Abdel-moneim, "Effect of dust on the transparent cover of solar collectors," vol. 47, pp. 3192–3203, 2006.
[19] V. Rajasekar, S. Boppana, and G. Tamizhmani, "Angle of incidence effect on five soiled modules from five different PV technologies," 2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015, 2015.
[20] J. J. John, V. Rajasekar, S. Boppana, S. Chattopadhyay, A. Kottantharayil, and G. Tamizhmani, "Quantification and Modeling of Spectral and Angular Losses of Naturally Soiled PV Modules," IEEE J. Photovoltaics, vol. 5, no. 6, pp. 1727–1734, 2015.
[21] H. A. and R. G. Hassan Qasem*, Thomas R. Betts, Harald Müllejans, "Dust-induced shading on photovoltaic modules," Prog. PHOTOVOLTAICS Res. Appl., pp. 218–226, 2014.
[22] M. S. El-Shobokshy and F. M. Hussein, "Degradation of photovoltaic cell performance due to dust deposition on to its surface," Renew. Energy, vol. 3, no. 6–7, pp. 585–590, 1993.
[23] J. J. John, S. Warade, G. Tamizhmani, and A. Kottantharayil, "Study of soiling loss on photovoltaic modules with artificially deposited dust of different gravimetric densities and compositions collected from different locations in India," IEEE J. Photovoltaics, vol. 6, no. 1, pp. 236–243, 2016.
[24] Z. Ahmed, H. A. Kazem, K. Sopian, M. A. Al-goul, and H. Alawadhi, "Effect of dust pollutant type on photovoltaic performance," Renew. Sustain. Energy Rev., vol. 41, pp. 735–744, 2015.
[25] P. D. Burton and B. H. King, "Artificial soiling of photovoltaic module surfaces using traceable soil components," Conf. Rec. IEEE Photovolt. Spec. Conf., pp. 1542–1545, 2013.
[26] P. D. Burton and B. H. King, "Application and characterization of an artificial grime for photovoltaic soiling studies," IEEE J. Photovoltaics, vol. 4, no. 1, pp. 299–303, 2014.
[27] S. Boppana, V. Rajasekar, and G. Tamizhmani, "Working towards the development of a standardized artificial soiling method," 2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015, 2015.
[28] K. Brown, T. Narum, and N. Jing, "Soiling test methods and their use in predicting performance of photovoltaic modules in soiling environments," Conf. Rec. IEEE Photovolt. Spec. Conf., pp. 1881–1885, 2012.
[29] B. Jamil, A. T. Siddiqui, and N. Akhtar, "Engineering Science and Technology , an International Journal Estimation of solar radiation and optimum tilt angles for south-facing surfaces in Humid Subtropical Climatic Region of India," Eng. Sci. Technol. an Int. J., 2016.
[30] N. Martín-chivelet, "Photovoltaic potential and land-use estimation methodology," Energy, vol. 94, pp. 233–242, 2016.
[31] T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches," Renew. Sustain. Energy Rev., vol. 22, pp. 698–733, 2013.