Soiling and Dust Impact on the Efficiency and the Maximum Power Point in the Photovoltaic Modules

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Abstract

The installation of PV systems for optimum yield is primarily dictated by its geographic location and installation design to maximize solar exposure. However, there are other depending factors that arise in determining the system performance (efficiency and output). Dust is the lesser acknowledged factor that significantly influences the performance of the PV installations. PV modules are highly reliable. However, in polluted environments, over time, they will collect grime and dust. There are also limited field data studies about soiling losses on PV modules. The photovoltaic cells already have low conversion efficiencies in the range of 16% to 18% , the accumulation of sand and dust particles from the outdoor environment on their surface further reduces the generated output power. This is due to the reduction the solar radiation incident on the solar cell. Further dust changes the dependence on the angle of incidence of such radiation. This limitation makes photovoltaic cells an unreliable source of power for unattended remote devices, such as solar-powered traffic and other remote applications in environmentally hazard areas. For large-scale solar plants to maintain their maximum efficiency, the photovoltaic cells must be kept clean, which can be a challenging task in dusty environments. This paper is an insight into the losses caused by the accumulation of dust on the surface of photovoltaic modules and an attempt to analyze and quantify such losses based on the experiments conducted by various researchers all over the world.

1. Introduction

PV modules are highly reliable. However, in polluted environments, over time, they will collect grime and dust. There are also limited field data studies about soiling losses on PV modules. The inherent material property of this semi-conductor limits the PV system efficiency of the photovoltaic system to within 15–20% [1]. Appropriate

installation design (orientation, exposure, sun-tracers) to maximize solar insolation can potentially ensure sustained yield (electricity). However, these are vulnerable to, often overlooked, on-site omnipresent practicalities such as deposition of dust, bird droppings and water-stains (salts) can significantly degrade the efficiency of solar thermal installations. For PV installations a module efficiency is further reduced by 10–25% due to losses in the inverter, wiring, and module soiling (dust and debris). Studies related to dust accumulation is critical as a further decrease in the (practical) system efficiency will tend to make PV systems an unattractive alternative energy source, particularly for the larger domestic markets. Current research into characterizing deposition of dust and their impact on PV system performance is limited given the fact that dust deposition is a complex phenomenon and is influenced by diverse site-specific environmental and weather conditions [2]. Dust is a term generally applying to minute solid particles with diameters less than 500 mm.

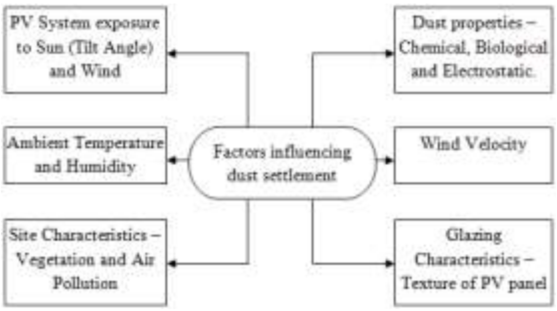

Figure 1 : Factors influencing dust settlement.

It occurs in the atmosphere from various sources such as dust lifted up by wind, pedestrian and vehicular movement, volcanic eruptions, and pollution. In the context of this paper, dust would also refer to the minute pollens (fungi, bacteria and vegetation) and microfibers (from fabrics such as clothes, carpets, linen, etc.) that are omnipresent and easily scattered in the atmosphere and consequently settle as dust. The characteristics of dust settlement on PV systems are dictated by two primary factors that influence each other, viz., the property of dust and the local environment. The local environment comprises site-specific factors influenced by the nature of prevailing (human) activities, built environment characteristics (surface finishes, orientation and height of installation), environmental features (vegetation type) and weather conditions. The property of dust (type – chemical, biological and electrostatic property, size, shape and weight), is as important as its accumulation/aggregation. Likewise, the surface finish of the settling surface (PV) also matters. A sticky surface (furry, rough, adhesive residues, electrostatic buildup) is more likely to accumulate dust than a less sticky, smoother one. It is also a well known that dust promotes dust, i.e. with the initial onset of dust, it would tend attract or promote further settlement, i.e. the surface becomes more amenable to dust collection.

Taking into account the effect of gravity, horizontal surfaces usually tend to accumulate more dust than inclined ones [3]. This however is dependent on the prevalent wind movements. Generally a low-speed wind pattern promotes dust settlement while a high-speed wind regime would, on the contrary, dispel dust settlement and have a cleaning. However, the geometry of the PV system in relation to the direction of wind movements can either increase/decrease the prospects of dust settlement at specific locations of the PV system. Dust is likely to settle in regions of low-pressure induced by high-speed wind movements over inclined/vertical surface. The dispersal of dust attributed to wind movements and geometry of PV system depends on the property of dust (weight, size, type). A framework to understand the various factors that govern the settling/assimilation of dust is illustrated in Fig. 1. It is easy to discern that the phenomenon of dust settlement is extremely complex and challenging to practically handle/comprehend given all the factors that influence dust settlement [4].

Table I illustrates field experimental observations by various researchers and the conclusions, which are very useful information at the design stages [5]. Being in an urban environment in an arid climate, PV systems can suffer dramatic losses between rain events due to the

2. Field Observations

Geographical Location	Observation/ Experiment	Conclusion
California and Desert Southwest, USA	PV efficiency declines by 0.16 percent per day between significant rainfalls. Light rains causes Efficiency and output power to reduce significantly while others (Not quantified) improves efficiency dramatically. Courtesy : Mitchell	Annual energy loss between 2.5 to 6.0 percent.
Reagan National Airport Washington DC	Observation : After 3 Years. Task : Cleaning the surface of PV Module. (Courtesy : Southwest Technology Development Institute)	The output power Pout increased by 23%.
Los Angeles, USA	Module cleaning (Courtesy : Kimber)	Annual system losses was 5 percent

Table 1 : Field observations by various researchers.

accumulation of soiling. Unusual soiling such as iron dust, plant matter, and bird droppings can create semi-permanent losses that are not fully recovered from even severe rain events. Depending on the severity of the pollution deposition and the cost/difficulty of cleaning, one or two cleanings during the dry season should accomplish both short

Geographical Location	Observation/ Experiment	Conclusion
50 m from a rail line.	High levels of iron dust from the railway lines. After four years of gradual decline in output reduced to 8 to 10 percent. After modules cleaning most of the power loss were reversed. (Courtesy : Haberlin)	Cleaning should be a frequent step as part of preventive maintenance.
Global	Bird droppings (Courtesy : Hammond)	Losses were , approaching 8 % and were not recovered fully even by heavy rain.

TABLE II : Continuation of Table I

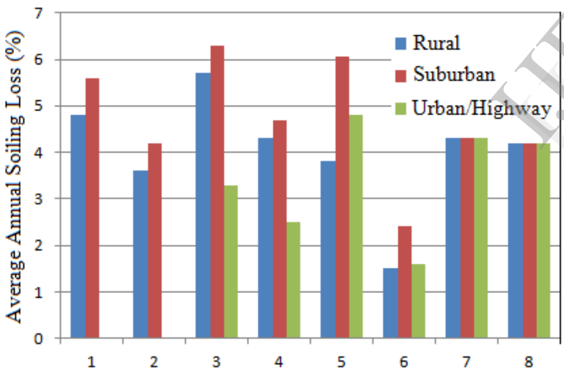

Figure 2: Average Daily Soiling Loss by Region and Environment (Source: Proceedings of the 4th World Conference on Photovoltaic Energy Conversion)

term and long term goals of reclaiming losses due to soiling from various sources. The numbers in the X axis, 1 to 8 represents the following cities.

1. South California Los Angeles
2. South California San Diego
3. Central Valley Sacramento
4. Central Valley Fresno
5. North California San Francisco
6. North California Petaluma
7. Desert/Southwest Las
8. Desert/Southwest Vegas Phoenix

Figure 2 shows the average daily soiling loss by region and environment [6].

3. Irradiation Losses

The evolution of the irradiation daily losses along the year of measurements is shown in Fig. 2. These losses (*HL*) represent the fraction of daily energy that a PV module will not receive as consequence of dust deposited on their surface, and are calculated as

$$HL(\%) = 100 \times \left(\frac{H_{CC} - H_{DC}}{H_{CC}} \right)$$ - Equation 1

where *Hcc* is the daily irradiation measured by the clean reference solar cell (W h m^{-2}) and *HDC* is the daily irradiation measured by dirty cell (W h m^{-2}). As can be seen in Fig. 2, the losses produced by the presence of dust are strongly dependent on the rainfall. In rainfall periods, a good cleaning of the dirty cell is produced and it recovers its initial performance; even a light rain, below 1 mm, is enough to clean the cover glass, reducing daily losses *HL* below 5%. However, in long periods without rain, like summer, the accumulation of dust can cause daily losses exceeding 20%.

Accumulations of dust on the surface of a photovoltaic module reduce strongly the energy received [7]. We have not observed any influence of the wind speed or direction on the losses, probably because the high relative humidity contributes to the adherence of the dust particles on the module surface. As shown in previous studies, these losses should not be constant during the day, but have to be dependent on the incidence angle of beam radiation. In order to study this dependency, irradiation values sensed by the clean and the dirty cells throughout the day are compared. In this case, relative irradiance losses are calculated as [8]:

$$GL\ (\%) = 100 \times \left(\frac{G_{CC} - G_{DC}}{G_{CC}} \right)$$ - Equation 2

where G_{CC} is the irradiance value measured by the clean reference solar cell (Wm^{-2}) and G_{DC} is the irradiance value measured by the dirty reference solar cell (W m^{-2}). It should be pointed out that losses caused by the dependence of the transmission coefficient of the glass cover on the angle of incidence does not affect in the calculation of *GL* since it is identical in both cells. However, the presence of dust modifies the angular dependence of the irradiance, which is different for the clean and the dirty cell, and precisely this effect is measured with *GL.* These losses represent the fraction of irradiance that the cell will not receive, and in the case of PV modules, power losses. When cells are clean, losses are approximately constant during the day. As dirt is deposited on the dirty cell, the behavior of the losses is not constant throughout the day in clear sky days, becoming dependent on the angle of incidence. Figure 3 shows the insolation losses corresponding to each tilt angle. The insolation values were calculated over a three-month period from January to March of 2011. The bars represent the

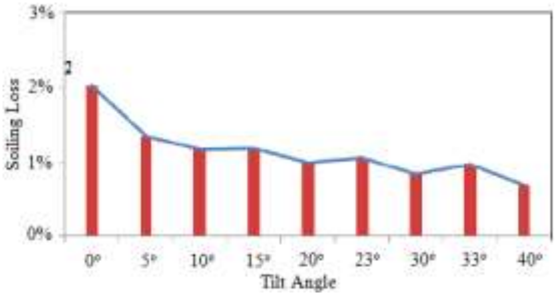

Figure 3: Soiling losses for each tilt angle from January to March, 2011at Arizona, USA.

complete average for the three months for each particular angle. First, the daily difference is calculated for each day starting from January 11th to March 31st. Then, the average is calculated for those values, represented by these bars. The graph signifies a decline in insolation loss as the tilt angle becomes more oriented towards latitude. As the tilt angle becomes increasingly horizontal, the insolation loss or soiling effect increases. Energy losses vary from 1% to 4% with horizontal solar modules. For the latitude of 33° energy losses are not as great, but still vary from up to 3%, depending on the daylight conditions the amount of time it has been accumulating soil before rainfall. Rainfall makes a difference, because rain can act to clean the modules. This cleaning action generally only occurs when rainfall surpasses a certain value of approximately 4-5 mm per day

4. Experimental Outcome and Analysis

Figure 4 shows the set-up of our experiment. It is based on the simple solar-cell experiment proposed by Morgan *et al* [9]. It consists of determining the approximate maximum power point of a photovoltaic panel under various states of dust accumulation and determining the loss of conversion efficiency compared with a clean photovoltaic panel. The set-up consists of a 12 cm by 8 cm photovoltaic panel with a maximum output voltage of 3 V, a decade box of resistors ranging between 0 and 330 Ω, two digital multimeters, a 200 W incandescent light source and a digital scale with a resolution of 0.01 g. Figure 2 shows the circuit for determining the maximum

Figure 4: Set up of our experiment.

power point of the photovoltaic panel. The maximum power point tells us the load at which the panel outputs its maximum power. The initial step of the experiment involves determining the maximum power point when there is no dust

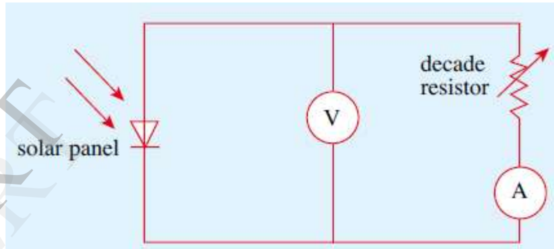

Figure 5: Circuit diagram for determining the effect of dust on the conversion efficiency.

accumulation on the panel. Prior to starting the experiment, we positioned the solar panel horizontally and away from and normal to the surface of the panel. The resistance on the decade box was set to its maximum value, 330 Ω, and the values of both current and voltage were recorded in milliampere and volts, respectively. Current through the circuit was then increased by setting the resistance to lower values, which in our case we set the decade box to 100, 33, 10, 3.3, 1, 0.33, 0.1 and 0 Ω, and manually recorded both the corresponding current and voltage. It is important to conduct the experiment in a short period of time to minimize the effect of temperature on the power output of the photovoltaic panel. Once the data were recorded, the power output of the panel ($P = VI$) for each load setting was determined. In our experiment, in the case of no dust accumulation on the panel, the approximate maximum power of 302 mW was achieved at a load of 10 Ω.

To examine the effect of dust, add 0.1 g of finely ground clay (bentonite) randomly over the photovoltaic panel and repeated the procedure described above. With 0.1 g of clay covering the photovoltaic panel, it was recorded a maximum power output of 272 mW at a load of 10 Ω. By adding more clay, where for a total of 0.2 g and 0.3 g of clay accumulated on the panel, it was recorded recorded a maximum power output of 255 mW and 241 mW, respectively, both at a load of 10 Ω. In the absence of bentonite, fine sand, icing sugar or finely ground chalk can be used. With all data recorded, the loss of conversion efficiency can be calculated using the formula

$$\eta_{loss} = 1 - \frac{P_d}{P_{nd}}$$

Equation 2

where *P*d is the maximum power output of the

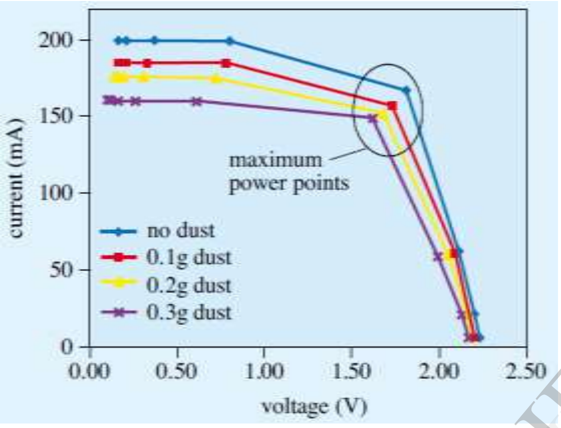

Figure 6: V-I curve for different amount of dust accumulation.

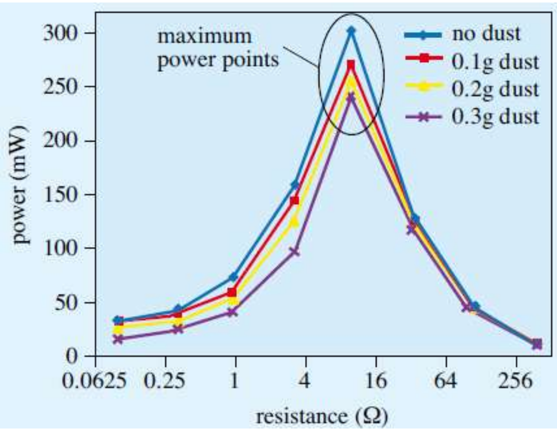

Figure 7: Change in maximum power points for different amount of dust accumulation.

photovoltaic panel with dust accumulation and *P*nd is the maximum power output with no dust accumulation on the panel. In our experiment for 0.1 g, 0.2 g and 0.3 g we saw a respective 10%, 16% and 20% loss in energy conversion efficiency. Figures 6 and 7 graphically illustrate the results obtained from our experiment in the form of current–voltage and power versus load resistance curves [9].

In practice, there are a number of factors which cause the actual operating point to vary from the algorithms to find the MPP have to move constantly around this optimal point thus operating the array off of MPP for some period of time. Search algorithms use finite time and voltage or current steps that may cause some error. These MPPT inaccuracies conspire to reduce the conversion efficiency of the PV array, and therefore, the entire system [10]. For best utilization, the photovoltaic cells must operate at their maximum power point (MPP). So, the maximum power point tracking (MPPT) is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics. The conventional research focus on the impact of temperature and irradiance on the MPP. But figure 5 shows the impact of dust on the MPP.

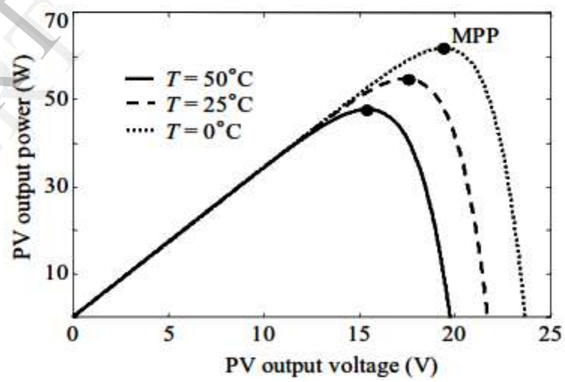

Figure 8: PV output voltage versus output power at different temperatures.

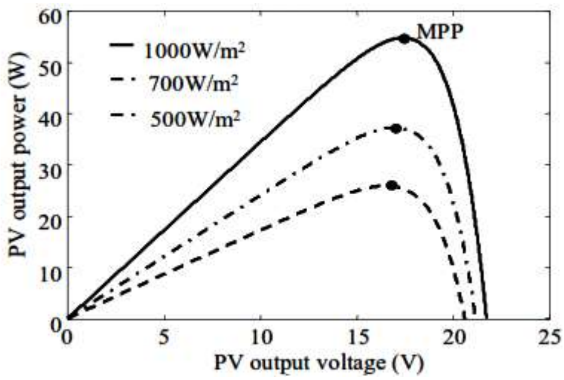

Figure 9: PV output voltage versus output power for different solar irradiance.

Figure 8 and 9 plotted by Matlab software [11], give the variation of typical PV module power-voltage characteristics of a PV module as a function of irradiation and temperature. It can be observed that the temperature changes mainly affect the PV output voltage, while the irradiation changes mainly affect the PV output power.

MPPT performance is important to system designers who are guaranteeing a certain system performance and need to know all of the system losses as well as to system operators who want to ensure that their system is operating per its specifications. Usually, Static and dynamic factors influencing MPPT behaviour include [12]: power (irradiance level), voltage (temperature; layout including well- or mismatched PV and MPPT voltage ranges), fluctuations (clouds), PV technology (I-V curve shape) , need (battery state of charge, in case of charge controller with MPPT). But figure 10 clearly indicate in the influence of dust on the MPP value of PV system.

From figure 10, it can be justified that the dust versus PV module efficiency graph follows an exponential curve of the form 1- ab^{x}, where, a > 0 and 0 < b <1. It also follows an exponential limited growth of the form which is theoretically plotted in figure 12.

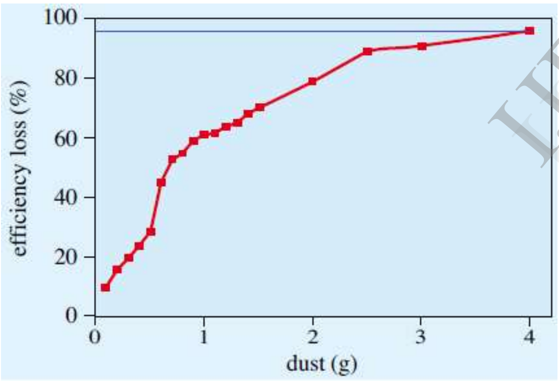

Figure 10 : The efficiency loss curve with respect to increase in dust accumulation.

The behavior can be also approximately modeled as a straight line Y=mx +c, with Y intercept c=20% or 0.2. This reveals that the dust always make a minimum of 20% loss in efficiency. A regular preventive maintenance can improve the efficiency to a better and constant level. The expression for the exponential limited growth can be stated as

$$y = ce^{-kt}$$
$$c, k > 0$$

- Equation 3

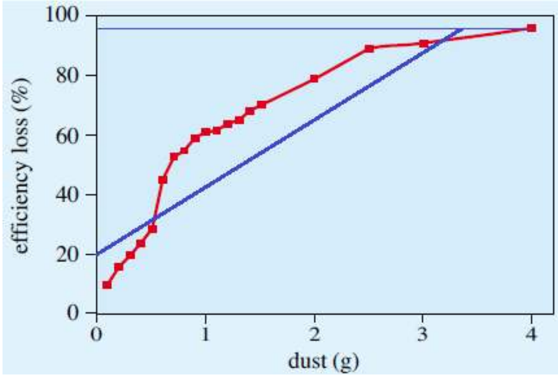

Figure 11 : Straight line model of the efficiency loss curve with respect to increase in dust accumulation.

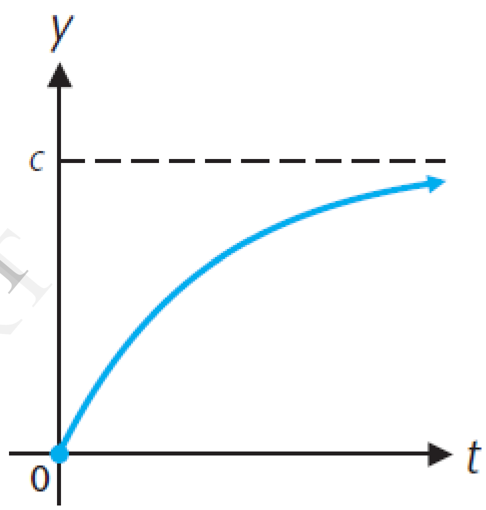

Figure 11 : The exponential limited growth model of efficiency loss.

On comparison of figures 10 and 12, the value of c can be determined from the graph as 0.95.

5. Conclusion and Future Scope

The installation of PV systems for optimum yield is primarily dictated by its geographic location and installation design to maximize solar exposure. However, there are other depending factors that arise in determining the system performance (efficiency and output). Dust is the lesser acknowledged factor that significantly influences the performance of the PV installations. PV modules are highly reliable. However, in polluted environments, over time, they will collect grime and dust. There are also limited field data studies about soiling losses on PV modules. The photovoltaic cells already have low conversion efficiencies in the range of 16% to 18% , the accumulation of sand and dust particles from the outdoor environment on their surface further reduces the generated output power.

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In an arid climate, PV systems can suffer dramatic losses between rain events due to the accumulation of soiling. Unusual soiling such as iron dust, plant matter, and bird droppings can create semi-permanent losses that are not fully recovered from even severe rain events. Depending on the severity of the pollution deposition and the cost/difficulty of cleaning, one or two cleanings during the dry season should be made.

In practice, there are a number of factors which cause the actual operating point to vary from the algorithms to find the MPP have to move constantly around this optimal point thus operating the array off of MPP for some period of time. Search algorithms use finite time and voltage or current steps that may cause some error. These MPPT inaccuracies conspire to reduce the conversion efficiency of the PV array, and therefore, the entire system. For best utilization, the photovoltaic cells must operate at their maximum power point (MPP). So, the maximum power point tracking (MPPT) is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics. The conventional research focus on the impact of temperature and irradiance on the MPP. But in this analysis the effect of soil an dust an MPP also analysed which a crucial factor in highly polluted Indian environmental conditions.

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