Effect of Dust on Photovoltaic Performance: Review and Research Status

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Abstract: - The electricity generation around the world is mainly produced by using non-renewable energy sources especially fossil fuel. However, these resources will be gone at some time in the not-too-distant future. Solar energy can be collected to produce electricity by a variety of methods. Among these methods, photovoltaic PV systems have shown great success due to many reasons. To name some, it is the oldest and most thoroughly researched, and has been tested and implemented for a long time across the globe. Implementations of PV systems have shown that their reliability and efficiency depend on many factors, the dominant being geographical (latitude, longitude, and solar intensity), environmental (temperature, wind, humidity, pollution, dust, rain, etc.) and the type of PV used. Dust is the slighter acknowledged factor that significantly influences the performance of the PV installations. The important of this study came due to the transfer of large scale PV technology to the desert area in Arab countries. This area is hot and dusty most of the time and dust represent the main barrier to PV utilization. This paper revises the research in studying the impact of dust on PV system performance.

Key-Words: - Dust deposition effect, Photovoltaic, Air pollution, Temperature, Humidity, Air velocity

1 Introduction

The PV solar power represents one of the most promising renewable energy in the world [1]. There are different types of PV cells which make solar modules: crystalline silicon, multi-crystalline (multi-c), mono-crystalline (mono-c), amorphous silicon (a-Si), etc. PV technology is well-proven for producing electricity [2]. PV systems can be either grid connected (with electricity fed directly into the grid system) or PV systems used in off-grid applications in small power systems in combination with diesel power gen-sets. Solar PV technology is especially suitable for electricity generation in off-grid power plants in rural desert areas and the use of solar energy in such hybrid systems can reduce diesel fuel use. The output of PV is rated by manufacturers under Standard Test Conditions (STC), temperature = 25 ^{o}C; solar irradiance (intensity) = 1000 W/m^2, and solar spectrum as filtered by passing through 1.5 thickness of atmosphere. These conditions are easily recreated in a factory but the situation is different for outdoor. With the increasing use of PV systems it is vital to know what effect active meteorological parameters such as humidity, dust, temperature, wind speed; etc has on its efficiency. This paper investigates the effect of dust on PV system performance. Monto and Rohit have revised the effect of dust on PV performance based on two time periods: from 1940-1990 and 1990-2010 [3]. This study revised the effect of dust based on the two periods while our paper discussed the effect based on three main points: effect of dust properties, effect of PV system parameters and effects of environmental parameters. So investigation of the direct effect of dust and the other parameters added to the dust to produce compound effect is the aim of this paper.

2 Effect of Dust Properties

The first point to be investigated is the effect of dust properties on the PV performance. This section separated into two main points: dust accumulation, and dust pollutant.

2.1 Dust Accumulation

Sand and dust particles deposition on PV surface in dry region are presented with numerical and analytical models by Neil [4] and supported by a laboratory investigation of sand particles accumulation on a glass surface. The accumulation of sand particles on horizontal glass surface is found to exponentially reduce the available area for transmission of incident photons. A grain threshold algorithm in the software Gwyddion was used to

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determine the fractional area of glass covered by particles. Figure 1 shows that the available free area on the glass slide decreases with increasing amounts of sand both before and after a gentle disturbance caused the sand structures to settle. The rearrangement effect becomes more pronounced with increasing sand accumulation, as a result of clustering and the formation of upper layers of particles.

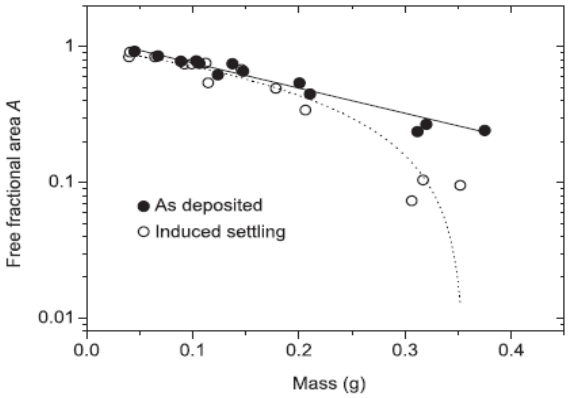

Fig. 1 Reduction in the free fractional area of a glass slide with increasing quantities of sand [4].

Filled circles in figure 1 show the ash-deposited coverage while open circles show coverage after application of gentle disturbance to the glass slide. The solid and dotted lines are exponential and linear fits to the data respectively.

Initially all sand particles are distant from each other and subsequent particles landing on them cannot be supported and fall onto the glass. In this regime the free surface area decreases linearly with sand mass. As more particles arrive on the surface, clusters are gradually formed and there is an increasing probability that subsequent particles will land on a cluster rather than on the glass. This causes the evolution of the free surface area to deviate from the linear behaviour described by Al-Hasan [5]. The model which is describe this process, consider adding particles of an arbitrary shape to a slide. The total area of particles deposited as a fraction of the total area of the slide is N, and is directly proportional to their mass.

The free fractional area A is not simply $1-N$ because particles overlap. This behaviour can be represented mathematically taking into account the probability that small particles lands on free surface area is $1-A$, such that

$$\frac{dA}{dN} = 1 - A \Rightarrow A = 1 - e^{-N} \quad (1)$$

There are important differences however between this simple model and reality. In particular, it is clear that there is a limit to how closely grains can pack together and that some, but not all sand grains can support a second grain. Recalling that the close packing factor must be used to connect particle area N and filling fractions F_1 and F_2, the evolution of the layers (i) is described by

$$\alpha \frac{dF_1}{dN} = 1 - c(F_1) \quad (2)$$

$$\alpha \frac{dF_2}{dN} = c(F_1)[1 - c(F_2)] \quad (3)$$

where α represent random close packing fraction ~ 0.8 and the fractional filling level of a given layer (i), (F_i) a layer can contribute to obscuring the surface is αF_i, $c(F_i)$ is the cluster function describe the fraction of sand grains that sit within a cluster. The total area is given by

$$A = 1 - \alpha F_1 - (1-\alpha) F_2 \quad (4)$$

This model has been used to investigate dust accumulation in dry regions which are in quantitative agreement with laboratory investigation on particle accumulation on a glass slide.

2.2 Dust Pollutant

The air pollution is degradation of PV performance as a result to accumulation of solid particles varying in type, composition and shape. Kaldellis and Fragos [6] conducted an experimental study to compare the energy performance of two identical pairs of PV-panels; the first being clean and the second being artificially polluted with ash, i.e. a by-product of incomplete hydrocarbons' combustion mainly originating from thermal power stations and vehicular exhausts.

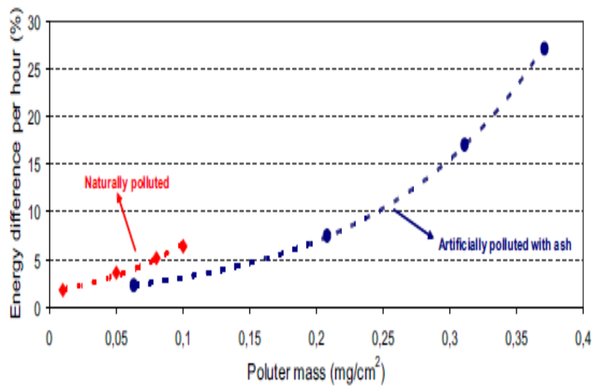

Fig. 2 Energy difference between clean and the polluted pair panel for various mass deposition in cases of naturally and artificially polluted PV[6].

Figure 2 shows the impact of different mass deposition of ash on PV's energy performance

which is decrease between the clean and polluted panels varying between 2.3% and 27% as it has recorded with time period of 1h.
Similar study by same authors [7], systematic experimental study of the pollution deposition was conducted to investigates the performance of two identical pairs of PV panels, the first panel being clean and the second being artificially polluted with three different type of air pollutants namely red soil , limestone and carbonaceous fly-ash particles. The experimental study was carried out under same environmental conditions as (ambient temperature, solar radiation, humidity etc,). According to the results obtained, it was found that the decreasing magnitude depending on the type of pollutant (i.e. composition, colour, diameter etc.). Based on the results, red soil deposition on PVs' surfaces causes the most considerable impact on PVs' performance and thus the highest generated energy reduction, followed first by the limestone and secondly by the carbon-based ash. Specifically, an amount of 0.35 g/m^2 of red soil deposition on PV-panels' surfaces may reduce the generated energy by almost 7.5% (compared with the respective of the clean one) while approximately the same deposition density for limestone 0.33 g/m^2 causes almost 4% energy reduction. On the other hand, even if almost doubling the pollutant mass for ash 0.63 g/m^2 the generated energy is decreased by only 2.3%. This may be explained due to the colour, composition and used diameter range of red soil causing the PV-panel to operate with lower performance.
Figure 3 shows the resulting energy yield reduction percentage between the clean "E_c" and the polluted "E_p" pair panel (adjusted in same tilt angle) as a function of different mass densities of red soil, limestone and carbon-based ash.

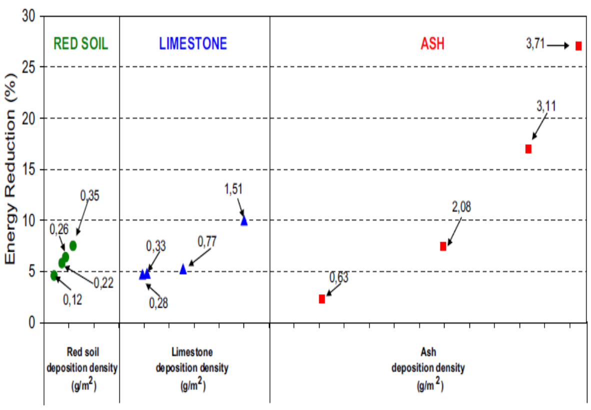

Fig. 3 Energy yield reduction of the polluted pair panel due to the different pollutants mass deposition in (g/m^2) [7]

In Fig 3 there is a strong indication that red soil deposition on PV-panels leads to rather worse results compared with other two pollutants. It seems that the generated energy strongly reduces with the red soil deposition on PVs' surfaces while the effect is slightly smaller for limestone and considerably smaller for carbon-based ash.
Hussein *et al* [8] have investigated experimental the effect of three types of dust pollutants (red soil, ash and sand) on the performance of PV panels (mono-c, multi-c and a-Si technologies investigated). The authors claimed that ash have the highest effect in comparison with other pollutants. Also, it is found that a-Si is performing better than mono-c and multi-c in dusty environment as shown in Fig. 4.

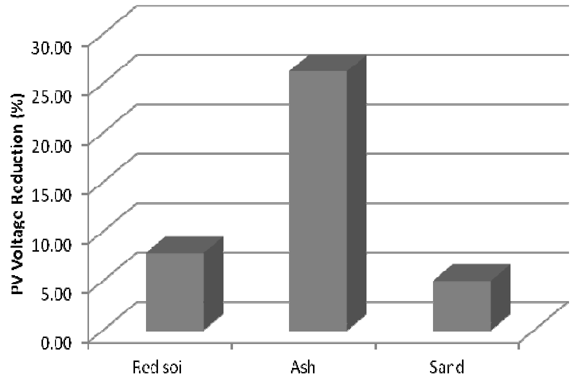

Fig. 4 Reduction in PV voltage due to the three pollutants [8]

Kaldellis and Kapsali [9] have developed a theoretical model in order to be used an analytical tool for obtaining reliable result concerning the expected effect of regional air pollution on PVs' performance. Air pollution represented by red soil, limestone and carbon-based ash related to previous study. In addition to, experimental concerning the dust effect on PVs' energy yield in a more polluted from air pollution urban environment is used to validate the proposed theoretical model.
Conversion efficiency "η" is defined as the ratio between the produced power " P_{out}" and the incident solar power "P_{solar}" available in collector's surface "A_c" . Thus

$$\eta = \frac{P_{out}}{P_{solar}} = \frac{P_{out}}{A_c . G_T} = \frac{U.I}{A_c . G_T} \qquad (5)$$

where "G_T" being the corresponding total solar radiation. "I" current and "U" the output voltage normally comprising a function of time "t" in order to calculate the generated power of installation.
The dust deposition "ΔM "is expressed in g/m^2 ,via the PV collector area "A_C" , as;

$$\Delta M = \frac{\Delta m}{A_c} \quad (6)$$

where Δm is the total mass of dust layer on the surface of the polluted pair of PV- panels.

Capacity factor "*CF*" (or energy yield) is defined as the ratio between the actual and rated output over a period time "Δt" as

$$CF = \frac{E_{\Delta t}}{P_P.\Delta t} \quad (7)$$

where P_P is the peak power.

Energy yield reduction percentages between the clean "CF_0" and the polluted "CF" pair panel as a function of different mass deposition densities for red soil, limestone and carbon-based ash for each examine case is expressed as:

$$\Delta(CF) = \frac{CF_0 - CF}{CF_0} \times 100 = \frac{E_{cl} - E_{pol}}{E_{cl}} \times 100 = \Delta E \quad (8)$$

Deposition of dust particles on the PV panels lead to an extra amount their energy performance, the rate of which depends strongly on the type of pollutant.

At this point, an attempt is made to simulate the PV-panels' energy yield (or capacity factor) drop on the basis of the air pollutant type (i.e. red soil, limestone and flying ash) and the corresponding specific mass deposition"ΔM". In order to develop a reliable and practical relation an exponential function of the general form:

$$CF_j = CF.e^{-A_j.\Delta M_j} \quad (9)$$

where "A_j" is the coefficient of standard deviation of mass measurements as in table 1 and the ranges between 0.06 and 0.24 depending on the type of pollutant "*j*", while "CF_j" is the capacity factor of polluted pair of panels for specific pollutant mass deposition "ΔM_j" (in g/m^2).

Table 1 Coefficient "*A*" and standard deviation

pollutant	A_j
Ash	0.06±0.024
Limestone	0.10±0.034
Red soil	0.24±0.085

In same context, the efficiency difference "$\Delta\eta$" between the polluted and the clean pair of PV-panels is defined as:

$$\Delta\eta_j = \frac{P_0}{G_T.A_C} - \frac{P_j}{G_T.A_C} = \frac{E_0 - E_j}{G_T.A_C.\Delta t} = \frac{(CF_0 - CF_j)}{G_T.A_C} = \frac{CF_0.P_P}{G_T.A_C} \quad (10)$$

or equal

$$\Delta\eta_j = \eta_0.(1 - e^{-A_j.\Delta M_j}) \quad (11)$$

In order to calculate the total capacity factor reduction percentage "$\Delta(CF)$" as a result to accumulation dust particles on the PV-panels surface one may combine Eqs. 9 and 8 into the following approach

$$\Delta(CF) = \frac{CF_0 - CF}{CF_0} \times 100 = (1 - e^{-A_{eq}.\Delta M}) \times 100 = \Delta E \quad (12)$$

with "ΔM" in (g/m^2) being the total mass of dust accumulated on PV-panel's surface and coefficient "A_{eq}" depending on the mass content of dust for each pollutant "ΔM_j", i.e:

$$A_{eq} = \sum w_j.A_j \quad (13)$$

$$w_j = \frac{\Delta M_j}{\Delta M} \quad (14)$$

and

$$\sum w_j = 1.0 \quad (15)$$

3 Effect of PV System Parameters

3.1 Effect of Tilt Angle

A tilt angle is one of the important factors that determine the performance of PV panels. In an experiment carried out in Roorkee by Grag [10] discovered that gather dust on a glass plate decrease transmittance by average of 8% after an exposure period of 10 days. Hegazy [11] studied dust deposition on glass plate with different tilt angles as well as measured the transmittance of the plate under different weather conditions. It was found that degradation in solar transmittance depend on the tilt angle. Also, the work by Sayigh et al [12] of dust deposition on a tilted glass plate located in Kuwait city were found to reduce the transmittance of the plate from 64% to 17% for tilt angles ranging from 0^0 to 60^0 respectively after 38 days of exposure to the environment.

3.2 Effect of PV Technology

PV module is classified into two categories which are silicon crystalline and thin film. Each category of PV modules (solar cells) contain of different types. The types of silicon crystalline are monocrystalline, polycrystalline, hybrid silicon, emitter wrap through cell and silicon crystalline investment while amorphous silicon, cadmium sulphide or telluride and copper indium disellenide or copper gallium are the types of thin film. The investigations found that a-Si performs best in dusty environment [13].

3.3 Effect of Cleaning Methods

Dust is probable to stick on to the array by Van der Waals adhesive forces. These forces are very strong at the dust particle sizes expected. Cleaning method must be overcome these forces. There are four ways classified to remove dust the surface of solar panel namely natural, mechanical, electromechanical and electrostatic. More investigation and ideas are important to reduce the effect of dust.

4 Effects of Environment Parameters

4.1 Effect of Temperature with Dust

The efficiency of PV cell usually decreases with high ambient temperature on the cell. That means the electric power generated from the cell decreases. With temperature increasing I_{SC} increases slightly with temperature by about *6 µA per °C* for *1 cm²* of cell. A more significant effect is dependence of the voltage which decreases with increasing the temperature. Typically the voltage will decrease by *2.3 mV per °C per cell.*

The investigations found that PV output power affected by ambient temperature. The more clean and cool PV the high power generated and more efficiency [14]-[16].

4.2 Effect of Humidity with Dust

Study the effect of humidity on PV cell, two cases must take into account. The first case is the effect of water vapour particles on the irradiance level of sunlight and the second case is humidity ingression to the solar cell enclosure.

Three phenomena occur when light hits water droplets. It may be refracted, reflected or diffracted. These effects deteriorate the reception level of direct component of solar radiation [17]-[19].

Figure 5 shows the effect of the relative humidity on the reception of visible solar radiation. It seem that this variation is non linear and this effect lead to little variation in V_{OC} and vast variation in I_{SC} as in Fig 6.

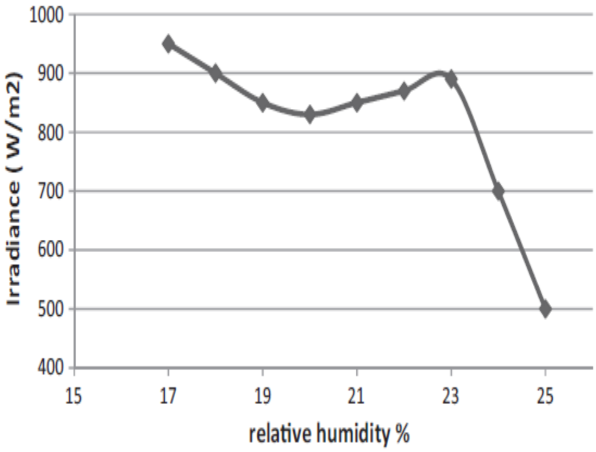

Fig. 5 variation of irradiance level with relative humidity [17]

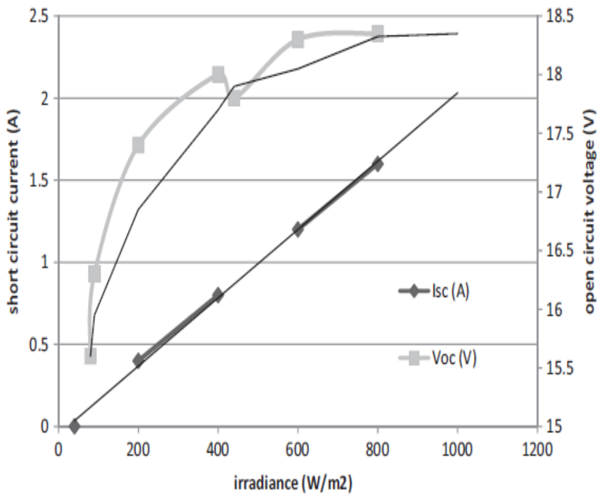

Fig. 6 variation of V_{OC} and I_{SC} with irradiance level [18]

The clear influence of humidity on irradiance and I_{SC} lead to decrease in efficiency according to equation:

$$\eta = \frac{I_{sc-\max} . V_{oc-\max}}{A_C (irradinace\ level)} \quad (16)$$

where A_C is the effective area of the module, I_{sc} is the short circuit current , V_{oc} is the open circuit voltage and η is the conversion efficiency.

The trend of wind speed has a reverse effect on relative humidity which in turn affects the received irradiance. For a long time exposure of PV modules

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to humidity leads to the ingress water into module and decrease performance [20].
In this context, delimitation with PV module is one of the most critical failure modes during service lifetime. Module of crystalline silicon most time fail at the cell interconnection or due to damaged cells while the thin film fail at scribe lines which is the dominate cause lead to modules degradation. Accordingly, thin films are sensitive to corrosive moisture while crystalline silicon cells are sensitive to embrillement of the encapsulant materials. Both of these degradation processes are increased by hot and humid weather [21]. The effect of dust increases in humid weather because they make together cement layer which make the cleaning process difficult task.

4.3 Effect of Wind Speed and Direction with Dust

Mamadow and Goosens [22] has used wind tunnel to determine the efficiency of sediment sampler designed to measure the deposition of aeolian dust. Marble Dust Collector (MDCO) and the inverted frisbee sampler were used in their investigation. Efficiency was ascertained for five wind velocities (range: 1–5 ms^{-1}) and eight grain size classes (range: 10–89 μm). They were presented formulate to determine the efficiency of an MDCO or frisbee when grain size composition of the sediment and wind's speed and direction are known. For the frisbee the equation:

$$E = au^6 + bu^5 + cu^5 + du^3 + eu^2 + fu + g \qquad (17)$$

where E = efficiency, u= wind speed (ms^{-1}), a, b, c, d, e, f, g numerical constant this formula validate to and wind between 0 and 7 ms^{-1}.
For the MDCO the equation:

$$E = p[\cos(2H) + q(4H)] + r \qquad (18)$$

where E = efficiency, H = orientation of the MDCO (rad); r, p, q are coefficients should be calculated. The last equation is validated to any speed between 1 and 7 ms^{-1}.

5 Conclusion

This paper reviews the effect of dust on the PV performance. The evaluation on the status of research has been discussed based on effect of dust properties, effect of PV system parameters and effects of environment parameters. Research conducted according to this classification highlight the impact of dust on the performance of PV. Some points are deeply investigated and some are still need more study. The main important points need more investigations are: dust properties (size, geometry, electrostatic deposition behaviour), biological and electro-chemical properties of dust, optimization study, for various geographical/climatic locations (latitude) considering factor of optimum tilt, altitude and orientation for solar gain, prevalent wind patterns and minimum dust accumulation for various PV module configurations, dust particle geometry on its deposition behaviour, electrostatic attraction on dust settlement behaviour, impact of progressive water-stains on degrading the PV performance.

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