# EFFECT OF DUST SHADING ON PHOTOVOLTAIC MODULES

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ABSTRACT: This paper investigates the effect of dust on photovoltaic (PV) modules with respect to dust concentration and spectral transmittance. Dust samples were collected from Kuwait in the form of raw dust and accumulated dust on sample glasses at different tilt angles. The spectral transmittance was measured at the Centre for Renewable Energy Systems Technology (CREST) laboratory with a spectrophotometer. Total transmittance variation was identified for samples at different tilted positions, where the worst case was presented at a tilt angle of 30$^o$ with a non uniformity of 4.4% in comparison to 0.2% for the 90$^o$ tilt between the top, middle and bottom. Finally the data was translated to an effective spectral response for different technologies using spectral response data measured by the European Solar Test Installation (ESTI). The measured data showed a decrease in transmittance at wavelengths <570 nm. This affects wide band-gap thin-film technologies more than crystalline silicon technologies and especially amorphous silicon which showed a 33% reduction in photocurrent when a dust concentration of 4.25 mg/cm$^2$ was applied. In comparison, the crystalline silicon and CIGS technologies showed 28.6% and 28.5% reductions at the same dust density.
Keywords: Dust, spectral response, amorphous silicon, CIGS, crystalline.

## 1 INTRODUCTION

In most arid zones of the world sand dust is a detrimental agent as far as solar energy applications are concerned. When foreign particles fall on PV modules, they interfere with illumination quality by both attenuating and scattering light. The degree to which the particles interfere depends on their constitution, density, and size distribution [1]. Particles impinge onto a surface under the influence of gravity and electrostatic charge or are carried there by wind or water droplets. After deposition, they are held by a charge double layer, surface energy effects, and capillary effects, in addition to gravity and electrostatic forces [2, 3].

Dust is one of the natural elements present in the environment. The variation in dust particle size and composition depends on the location [4]. In some regions, dusty weather conditions tend to be more severe than in others. For example, in Kuwait dust is present in 27% of daylight hours throughout May to August (see Figure 1). It causes deterioration in visibility during dusty days [2, 3]. Also, dust tends to settle, creating a fine layer of accumulated dust on any exposed surface. It was reported that different parameters support the accumulation of dust such as gravitational forces, wind speed, wind direction, electrostatic charges and the wetness of the surface [5]. Of those parameters, the most dominating are the gravitational effect, particle size and wind speed [10-12]. Slow wind speeds increase the deposition of dust, while fast help to remove dust if the wind is incident in an appropriate direction [5, 7].

The random accumulation of dust on the PV module surface area can produce spots with varying concentrations of dust particles, as illustrated in Figure 2. These spots vary in shape, location and concentration density. The variation in dust accumulation can lead to different transmittance of light into the module, thus leading to small random areas on the PV module with partial shading from incident solar radiation.

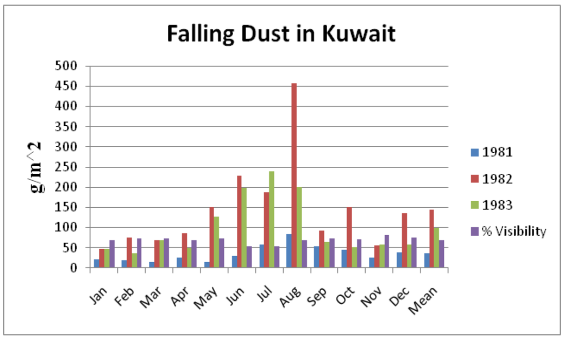

Figure 1: Falling dust in Kuwait international airport. A note here is that visibility does not always relate to falling dust. It can be a factor of humidity, rising dust, and suspended dust.

It has been reported that falling dust has a direct effect of reducing the performance of solar PV modules [1-17]. Both settled and airborne dust reduces the amount of solar radiation incident on the surface of a PV module [12]. Goosens and Van Kerschaever provide a relation between airborne dust, settled dust and the reduction in PV cell short circuit current. Using a wind tunnel experiment, they showed that there is an aerodynamic relation between airborne dust, accumulated dust and the reduction in PV power output [13]. Others have reported a relation between dust particle size, particle distribution, tilt angle and the reduction in transmittance of solar radiation [1, 6, 8, 11, 12]. In general, all these publications showed a reduction in short circuit current with increase in accumulated dust density.

**Figure** 2: Accumulated dust on different PV modules installed in Kuwait.

Most of the work reported in relation to dust has been with regard to modules direct output performance. Some papers suggested casual cleaning, static devices and optimization for tilt angle according to the dust information in the region [5, 15-17]. Others report a special glass coating that promotes self cleaning [18]. The cost effectiveness of these methods is not yet known, and it will require further investigation before deciding on an appropriate course of action. However, relatively little work has been done in identifying the variation of dust density on the tilted PV module and the effect of dust on different PV technologies. In this paper, a relation between spectral transmittance and dust density is established which will be used to identify the variation of dust density on tilted modules and the effect of dust on different PV technologies through the modification of the effective spectral response.

## 2 METHODOLOGY

Different works have been reported where correlation between dust and PV system output was shown [5]. In most cases, the measurement being taken was the output from PV modules in relation to percentage of accumulated dust or as a dust density. For our work, more quantitative measurements of dust were needed to be able to correlate it to module performance, which is why a new approach was used and is explained in the following sections.

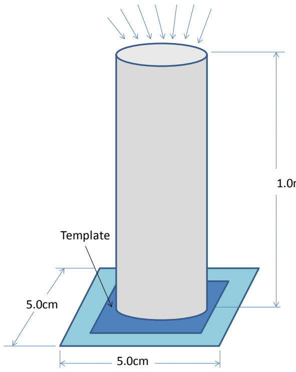


Figure 3: Dust deposition template on the glass sample using free fall.

Dust samples were collected using a collecting vessel that was left outdoors for a number of days in a dusty season in Kuwait. The collected dust was then deposited in the lab onto a 2.0cm x 2.0cm area using a 5.0cm x 5.0cm Soda Lime glass with a thickness of 1.0 mm. The deposition of dust was done by free fall from 1.0 m height using a cylindrical tube to minimize the effect of wind currents in the lab, see Figure 3. The weights of the samples were measured using a balance with sensitivity of 0.1 mg. Finally, the samples were encapsulated and the transmittance of each was measured using a spectrophotometer. The encapsulated sample spectral transmittance for randomly selected samples were repeated three times each to ensure repeatability, and to measure possible deviation in the measurements due to double glass encapsulation, reflection between the glass layers and the effect of electrostatic charges collected on the glass. It was noted that when the sample edges are shielded and grounded the average percentage difference between the shielded and non-shielded samples was 1.9%, and the average percentage deviation between the repeated samples improved from 7.5% to 1.8%. The transmittance of a clean (non-dusty) encapsulated glass sample was measured and used to correct the sample measurements (avoiding wavelengths below 300nm due to the filtering property of Soda Lime glass).

To investigate the effect of tilt angle, a number of 4.0cm x 4.0cm heat tempered glass samples were installed in a dusty environment in Kuwait for a period of one month. The samples were placed facing south, with tilt angles of $0^o$, $15^o$, $30^o$, $45^o$, $60^o$ and $90^o$. The samples were then encapsulated and divided conceptually for analysis into three sections: top, middle and bottom. The transmittance of each section of each sample was measured using a spectrophotometer. The spectral transmittance data obtained from the dust samples were then used to modify measured spectral response data from ESTI for 9 crystalline silicon (c-Si), 3 amorphous silicon (a-Si), 2 copper indium gallium diselenide (CIGS) and one cadmium telluride (CdTe) modules. The modified data are used to correlate the effects of dust on different PV technologies.

## 3 RESULTS AND DISCUSSION

### 3.1 Sediment characterization

The dust sample was collected in Kuwait during May 2010 for a period of 30 days. The sand grain size was then analysed using a microscope to determine the grain size distribution. This was parameterised using the Phi value, which uses ($-Log_2$ diameter of the particle) as the sorting criteria. The collected dust sample size distributions are shown in Figure 4.

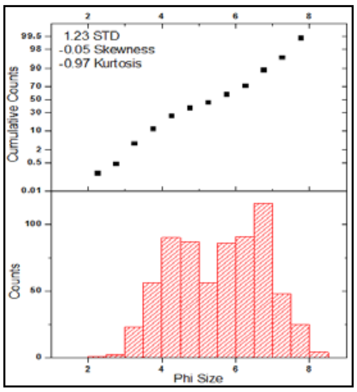


Figure 4: Probability distribution of the counted samples

The major grain size distribution was found to be of silt that was distributed between coarse, medium and fine silt (see Table 1). The majority of the silt grains were of slate, whereas the bigger grains were quartz.

Table 1: Dust grain distribution and size types

| Φ* | % of the total sample | Cumulative weight percent | Grain type |
|---|---|---|---|
| 0.0 - 1.0 | 0.0 | 0.0 | Coarse grained |
| 1.0 - 2.0 | 0.0 | 0.0 | Medium grained |
| 2.0 - 3.0 | 0.6 | 0.0 | Fine grained |
| 3.0 - 4.0 | 11.4 | 28.4 | Very fine grained |
| 4.0 - 5.0 | 25.8 | 40.7 | Coarse silt |
| 5.0 - 6.0 | 20.7 | 16.4 | Medium silt |
| 6.0 - 7.0 | 30.2 | 11.7 | Fine silt |
| 7.0 - 8.0 | 10.7 | 2.4 | Very fine silt |
| < 8.0 | 0.6 | 0.1 | Clay |

* $\Phi = -\text{Log}_2$ (diameter of the particle in μm)

3.2 Dust concentration

The dust sample transmittances were measured with a spectrophotometer over a wavelength range of 300nm to 1200nm as shown in Figure 5 and Figure 6. Any values under 300nm or higher than 1200nm are beyond our scope since the spectral response wavelengths used by most materials used in PV technologies are within the 300 nm – 1200 nm band.

In the 300 nm - 570 nm region, it was noted that transmittance dropped at a faster rate than that above 600nm as shown in Figure 5. The nudge in the transmittance curve happens during the lamp change in the spectrophotometer and it can be considered as measurement uncertainty.

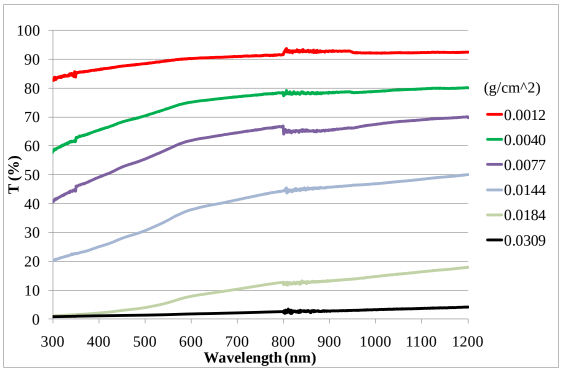


Figure 5: Spectral transmittance curves for different dust density samples.

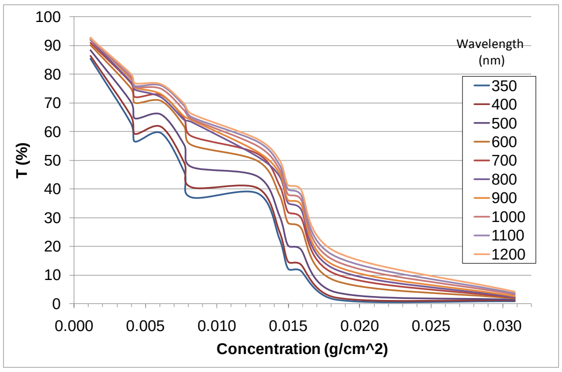


Figure 6: Variation of dust density with transmittance at different wavelengths.

In Figure 6, at dust density > 19 mg/cm$^2$ the effect of wavelength becomes minimal especially in the visible range. For wavelengths > 570 nm the variation between density-transmittance curves is 2.5% on average while for wavelengths < 570 nm the average percentage difference is 11%. So it can be said that at shorter wavelengths, the dust effect is more severe than at longer wavelengths.

3.3 Tilt Angle

The variation of dust accumulation on tilted surfaces was shown in the spectral transmittance data obtained from measuring the dust samples collected in Kuwait in the period from 9/9/2009-6/11/2009. The dust samples were encapsulated and spectral transmittance was measured at three different areas, top, middle and bottom see Figure 7.

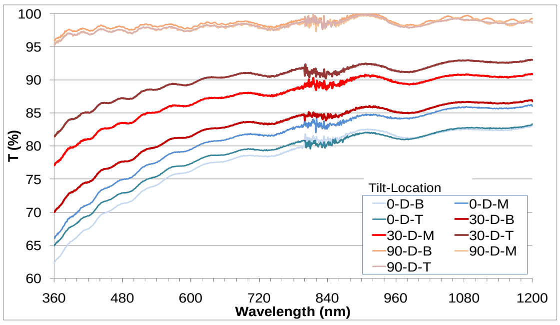


Figure 7: Spectral transmittance curves for different tilted samples at 0, 15, 30, 45, 60 and 90$^o$.

Two general trends were observed in the spectral transmittance data shown in Figure 7. The first trend shows that with increased tilt angle, dust accumulation decreases, this can be explained as gravity affecting dust samples more for higher tilt angles. The second trend is shown more clearly in Table 2, where transmittance through the tilted samples decreases toward the bottom. The 90$^o$ showed a non-uniformity of only 0.21%, in comparison to the 30$^o$ which showed 4.39% non-uniformity between the top, middle and bottom sections. The 0$^o$ showed a higher variation than that at 15$^o$. This can be attributed to the higher dust density of the 0$^o$ sample which made it more sensitive to environmental effects such as wind direction in comparison to the tilted samples.

Table 2: Non uniformity of transmittance at different tilt angles [%]

| 0$^o$ | 15$^o$ | 30$^o$ | 45$^o$ | 60$^o$ | 90$^o$ |
|---|---|---|---|---|---|
| 1.98 | 1.01 | 4.39 | 1.00 | 0.73 | 0.21 |

The variation of the transmittance through the tilted samples is clearly due to the variation of dust density at different locations in the sample. To identify the dust density, the spectral transmittance data for the tilted samples were fitted between the data measured in section 3.2 in the range of 1-4.5 mg/cm$^2$ dust density. The obtained density transmittance curves for the tilted samples are shown in Figure 8. The fitted dust density values shown in Table 3 agree with the results obtained in Table 2 where the sample tilted at 30$^o$ showed the worst case variation of 1.4 mg/cm$^2$ in dust density in comparison to the 90$^o$ with only 0.1 mg/cm$^2$ of variation between top, middle and bottom sections of the sample.

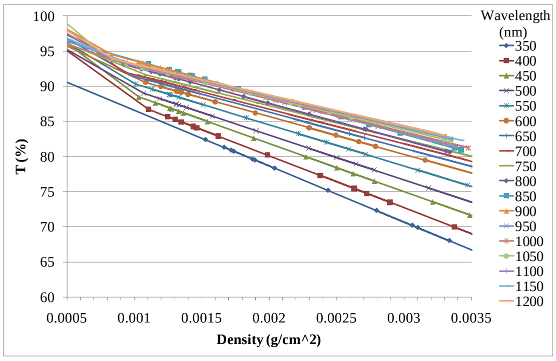


Figure 8: Transmittance density curves obtained by fitting the spectral transmittance curves for the tilted samples into measured dust density curves obtained in section 3.2.

Table 3: Fitted dust density (mg/cm$^2$) values for the tilted dust samples

| | 0° (mg/cm$^2$) | | | 15° (mg/cm$^2$) | | | 30° (mg/cm$^2$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | **B** | **M** | **T** | **B** | **M** | **T** | **B** | **M** | **T** |
| **AVG** | 3.6 | 3.0 | 3.5 | 2.4 | 2.1 | 2.4 | 2.7 | 1.8 | 1.3 |
| **MAX** | 4.3 | 3.8 | 3.9 | 3.1 | 2.8 | 3.1 | 3.3 | 2.4 | 1.9 |
| **MIN** | 3.2 | 2.6 | 3.2 | 2.0 | 1.8 | 2.2 | 2.4 | 1.5 | 1.0 |
| **STD** | 0.3 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| | **45° (mg/cm$^2$)** | | | **60° (mg/cm$^2$)** | | | **90° (mg/cm$^2$)** | | |
| | **B** | **M** | **T** | **B** | **M** | **T** | **B** | **M** | **T** |
| **AVG** | 1.1 | 1.5 | 1.3 | 1.3 | 1.2 | 1.0 | 0.3 | 0.2 | 0.2 |
| **MAX** | 1.7 | 2.0 | 1.9 | 1.7 | 1.7 | 1.5 | 0.5 | 0.4 | 0.4 |
| **MIN** | 0.9 | 1.2 | 1.1 | 1.1 | 1.0 | 0.8 | 0.03 | 0.04 | 0.05 |
| **STD** | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |

### 3.4 Spectral effect

The first step to quantify the effect that dust has on PV cells is to examine the effect of the transmittance curves on the spectrum. An International Electrotechnical Commission (IEC) [19] standard spectrum at 1000 W/m$^2$ and an air mass 1.5 was multiplied with the different spectral transmittance curves at 4.25, 14, 19, and 30 mg/cm$^2$ dust densities. The graph shows a clear effect of dust as a shading factor on different wavelengths which indicates that it has a potential spectral effect on PV devices further than just a blanket shading impact.

Spectral response data for different PV technologies supplied by ESTI was corrected for the different spectral transmittance curves obtained in sections 3.2 and 3.3. The corrected curves show a variation between different technologies with regard to the same spectral transmittance dust curves as shown in Figure 9, Figure 10 and Table 4. In Figure 9, samples of c-Si module spectral response data were corrected with 4 dust spectral transmittance curves while Figure 10 shows the same transmittance curves applied to a-Si, CIGS and CdTe PV modules. The spectral photocurrents shown in Table 4 were obtained by integrating the area under the product curve of AM 1.5 and the modified spectral responses in Figure 9 and Figure 10.

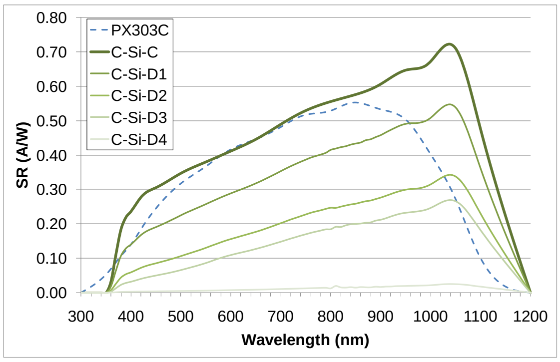


Figure 9: Spectral response of c-Si modules corrected for 4 different spectral transmittance dust curves, D1=4.25 mg/cm$^2$, D2=14 mg/cm$^2$, D3=19 mg/cm$^2$ and D4=30 mg/cm$^2$.

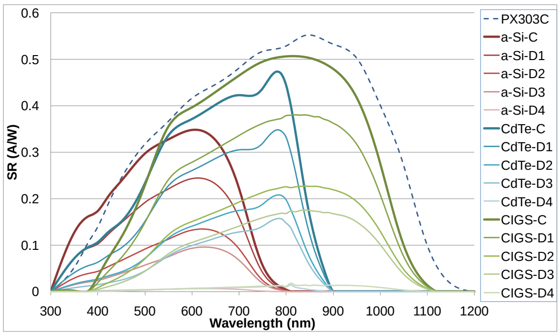


Figure 10: Spectral response of thin-film modules corrected for 4 different spectral transmittance dust curves, D1=4.25 mg/cm$^2$, D2=14 mg/cm$^2$, D3=19 mg/cm$^2$ and D4=30 mg/cm$^2$.

Table 4: Percentage difference variation between clean module data and those corrected for the spectral photocurrent.

| Density (mg/cm$^2$) | a-Si | CIGS | CdTe | c-Si |
|---|---|---|---|---|
| **4.25** | -33.0% | -28.5% | -30.1% | -28.6% |
| **14** | -66.0% | -59.6% | -61.9% | -59.6% |
| **19** | -77.4% | -70.6% | -73.1% | -70.6% |
| **30** | -98.4v | -97.8% | -98.1% | -97.8% |

From Table 4, we can see that a-Si and CdTe technologies are affected more than the c-Si and CIGS modules when they are covered with dust. This can be correlated to the high band gap of the affected modules that have effective spectral response ranges between 300 nm to 800 nm where the spectral transmittance through dust decreases more strongly than at longer wavelengths.

## 4 CONCLUSION

The relation between dust density and spectral transmittance shows trends where with high dust density (>38 mg/cm$^2$) the effect of wavelength becomes minimal. Another trend shows that at dust density < 19 mg/cm$^2$ the spectral transmittance curve shows two regions, >570 nm spectral transmittance data showed a minimal change in transmittance. The second region at wavelength <570 nm showed a stronger attenuation, with transmittance decreasing increasingly severely as wavelength becomes shorter.

The effect of tilt angle is directly related to the amount of dust density variation on the surface. The 90$^o$ tilt angle showed the least variation of dust accumulation of 0.1 mg/cm$^2$ due to the fact that gravity affects it the most and supports the process of dust removal over time. The sample tilted at 30$^o$, which is the optimal tilt angle for PV modules in Kuwait regarding sun position, showed the highest variation of dust accumulation of 1.4 mg/cm$^2$ with most of dust settling toward the bottom of the sample.

Dust contributes to the reduction of PV modules output by attenuating irradiance in a spectrally-dependent manner. This can be seen in the effect on the spectral response data. The effect is not the same magnitude for all types of PV technology because the spectral transmittance affects various spectral response shapes differently. The effect is worse for the PV modules with higher band gap such as a-Si and CdTe technologies which showed 33% reduction in photocurrent when a concentration of 4.25 mg/cm$^2$ of dust was applied. In comparison, c-Si and CIGS technologies showed 28.6% and 28.5% reductions at the same dust density.

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