Soiling of Photovoltaic Modules: Size Characterization of the Accumulated Dust

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***Abstract*—Soiling significantly reduces the energy production of photovoltaic (PV) modules. The reduction is not only determined by the amount and composition, but also by the size distribution of the particles. This study investigates the particle-size characteristics of dust accumulated on horizontal and inclined glass surfaces used in PV modules. The accumulated dust is compared to the ambient airborne dust. Effects of tilt angle and wind speed are investigated. Variations in particle size over the glass surface are also studied. Dust accumulating on a photovoltaic module is finer than ambient airborne dust, except for a combination of forward tilt AND low wind velocity. For wind velocities large enough to initiate wind erosion the accumulated dust is finer than the airborne dust even in the case of forward tilt. For backward tilt the accumulated dust is always finer than the airborne dust. Reasons for the finer dust are the preferential accumulation of the finer particles in the wake of the module due to their lower response time compared to coarse particles and the preferential removal of the coarsest fractions by the wind. At forward tilt accumulated dust is finest near the leading and trailing edges of a module whereas at backward tilt the particle size distribution over a PV module is more uniform. Energy prediction models should incorporate these internal variations and the differences with airborne dust.**

***Index Terms*—Dust, glass, particle size distribution, PV module, soiling.**

I. Introduction

Soiling, which can be broadly defined as the pollution of surfaces by several kinds of substances such as mineral particles, plant products, soot, salt, bird droppings, or growth of organic species [1], is an important problem in outdoor photovoltaic (PV) and concentrated solar power (CSP) stations. Soiling is particularly important in dry climates such as deserts, which are characterized by high aeolian activity. Most deserts are prone to an almost continuous precipitation of fine mineral dust particles. The year-round precipitation of dust results in pollution of the panels and mirrors, and consequently, in a decrease of their efficiency [2]-[4].

Although the impact of soiling on PV and CSP performance has already been recognized since the 1940s [5] it has received much attention over the last decade. Literature reviews can be found in [1], [6]-[15]. Various aspects of soiling have been treated, mostly focusing on the negative impact on PV performance. A topic that so far has received less attention, or at least has not yet been studied systematically, is the particle size and particle size distribution of the dust on PV and CSP surfaces. Its significance is substantial, however, for various reasons:

1) The loss in transmittance (for PV) or reflectance (for CSP) caused by soiling is not only determined by the thickness and cover density of the dust layer but also depends on the particle size and particle size distribution. Particle size is an important factor in the accumulated dust's ability to scatter and attenuate solar irradiation [16]. Most light scattering is done by the very fine particles [17], resulting in more light attenuation. Fine particles may also cause higher performance degradation of PV modules than coarse particles for the same mass of dust. This is because for a given mass, the number of small particles is larger, and so is the surface area they will cover so that less light will pass [18]-[20]. Soiling-related PV performance degradation does, therefore, depend on the particle size distribution of the dust deposited on the surface [13], [16], [21], [22].

2) The strength of the cohesion and adhesion forces that stick particles to each other and to PV and CSP surfaces depends, among other factors, on particle size and particle size distribution. For cohesion, the inter-particles forces are much higher for fine dust compared to coarse dust [23]. Moisture (dew, for example) significantly increases cohesion [24]. For adhesion the situation is more complex. The adhesion forces between adjacent particles and between particles and a PV surface are normally due to electrostatic forces, van der Waals forces and capillary forces [25]. Van der Waals forces dominate at low values of relative humidity whereas capillary forces dominate at higher values. It is commonly assumed that the adhesion forces increase with particle diameter [25]. Recent studies [26] show that although this is true for smooth particles such as spheres, it does not always seem to be the case for rough particles such as most natural dusts. One should also realize that the strength of the adhesion forces is also a function of surface roughness: the rougher the surface on which the particles are deposited, the lower adhesion becomes, both for smooth and rough particles [26].

3) The kinetic energy during particle impact on PV and CSP surfaces, and the resulting rebound and splash, depend strongly on particle size. Since kinetic energy is directly proportional to mass, it is much higher for coarse particles than for fine particles. Coarse particles impacting on a dust-covered PV or CSP surface will not only rebound better but will also cause more splash (the release of surface particles near the point of impact, see [27] or [28] for a detailed description of this process). Coarse particles will create a small spot of less dust near the point of impact, and this may result in a higher transmittance near that point. On the other hand, when coarse particles hit the glass or mirror

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surface at a high speed the impact may result into abrasion of the glass, or it may cause damage to anti-soiling and anti-reflective coatings. Impact of fine particles will cause less direct damage to the surface [29].

4) The response time of particles, and the resulting trajectories the particles follow when they arrive at, and flow over PV and CSP surfaces depend, besides on the fluid properties, on the particle characteristics including particle size [30]. Fine particles will show a tendency to follow the streamlines of the airflow whereas coarse particles will not. When arriving at, and flowing over PV or CSP constructions this will result into different deposition and accumulation patterns and amounts according to the specific size of the particles. Examples will be shown later on in this article.

Many studies report on the particle size of dust accumulated on PV surfaces. Inventories have been prepared by [14] and [31]. However, most of the collected studies report only general information, usually derived from a particle size analysis of samples collected from a specific outdoor PV construction. Most studies were not set up to specifically investigate the particle size characteristics of the accumulated dust. The technique adopted to measure the particle size distribution also varied quite substantially between these studies, and this is a problem since a different analysis technique may result in a different result even when applied to the same sample [32].

In a study by Kazmerski *et al*. [33] the particle size distribution of dust on a PV module was compared to the particle size distribution of airborne dust 1 m above the module. It was found that the dust on the module was considerably finer than the airborne dust. Sansom *et al*. [34] compared the particle size of airborne sediment collected in Iran, Libya and Algeria to sediment collected from CSP mirrors in Almeria (Spain) and concluded that the airborne sediment was coarser than the CSP sediment. Although this seems to confirm Kazmerski *et al.*'s findings, care should be taken because no airborne samples were collected in Almeria. Jiang *et al*. [35], on the other hand, reported that when airborne particles settle on a PV surface they may form aggregates, resulting in the formation of coarser dust.

Kluggmann-Radziemska [36] reported that the particle size distribution of dust on PV surfaces will depend on the tilt angle because coarse particles can roll off the panel's surface when the tilt increases, but no data were presented to confirm this statement. Sylvia [37] collected dust from PV modules in Las Vegas (Nevada, USA) and compared it with soil dust and airborne dust, but only for chemical composition and mineralogy and not for particle size or particle size distribution.

In conclusion, particle size and particle size distribution of dust on PV and CSP surfaces has been measured at many stations, but no systematic study has been performed so far to check the differences with airborne dust at the same location, or the potential differences (in particle size) that may occur within one and the same PV module or CSP mirror. To cite Sarver *et al*. ([14], p. 721): "The understanding of what is present in the airborne components and what gets deposited on the solar collector is one area that needs further research and development".

The purpose of this study is to investigate the particle size and particle size distribution of dust accumulating on a PV module. More specifically the work aims to answer the following questions:

1. What are the differences between the particle size characteristics of airborne dust and dust that accumulates on photovoltaic surfaces?
2. Does tilt angle affect the particle size and particle size distribution of dust accumulating on photovoltaic surfaces?
3. Are the particle size characteristics of accumulated dust uniform over a photovoltaic surface or do they vary over the surface?
4. Does the accumulation pattern of dust on a photovoltaic surface depend on particle size?

The answer to these questions is important because theoretical and physical models that calculate the electrical performance of PV installations, and the resulting energy yield, should consider both the amount and the particle size characteristics of any dust present on such installations.

To answer the questions, experiments were conducted in an environmental wind tunnel in which dust transport over, and dust deposition on PV surfaces can be studied under strictly controlled conditions. This work reports the results of this study.

II. Facilities and Instruments

A. Wind Tunnel

The experiments were carried out in the closed-return wind tunnel of the Geography and Tourism Research Group, KU Leuven, Belgium. This wind tunnel has been specially designed to study aeolian dust dynamics and contains two test sections. All measurements were performed in the largest test section, which is 760 cm long, 120 cm wide and 60 cm high.

B. Dust Cloud Producer

To create dust transport over the test surface an Engelhardt KDA-FS 300N laboratory dust cloud producer (KTG Engelhardt GmbH, Nürnberg, Germany) was connected to the tunnel. This apparatus ensures a continuous feed of dust particles to the airflow, and allows the operator to adjust dust discharge. The dust was added to the flow in the return section of the tunnel via a small but wide opening in the tunnel roof, 12 m upstream from the test setup. During its passage through the tunnel the dust is fully dispersed over the test section. The exact distribution of the dust at the location where the experiments were carried out is accurately known so that the appropriate corrections can be made when necessary.

C. Test Surface

All experiments were performed with an untextured and uncoated glass coupon 30 cm long, 17.5 cm wide and 0.2 cm thick. To allow investigating the variations in dust accumulation and particle size distribution that may occur over the coupon it was divided into five 20-cm wide and 3.5-cm long strips, oriented perpendicular to the airflow and located in the center of the coupon, with 5 cm unused space near each lateral border (Fig. 1). The strips were drawn with a

permanent marker, on the back side of the coupon (the side that was not used for collecting dust) to avoid any potential interference with the deposition and accumulation process. After each experiment, dust was collected from each strip separately.

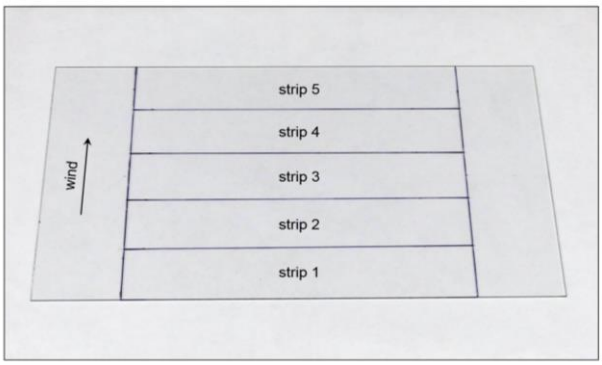

Fig. 1. Photo of the glass coupon with indication of the test strips. Each strip is 20 cm long and 3.5 cm wide.

D. Wind Measurements

Wind speeds were measured with an accuracy of 0.01 m s^{-1} using (1) a mini pitot tube (Vanderheyden, Brussels, Belgium) connected to a digital Furness FC016 manometer.(Furness Controls Ltd., Bexhill, UK), and (2) a Testo 0635-1048 hotwire anemometer (Testo NV, Ternat, Belgium). Turbulence was measured with the Testo 0635-1048 hotwire anemometer.

E. Particle Size Analysis

All particle size analyses were performed using laser diffraction. The instrument adopted was a Malvern Mastersizer S laser particle size analyzer (Malvern Panalytical Ltd., Malvern, UK). We opted for laser diffraction because this technique provides great detail, shows excellent repeatability, allows very fast measurements, and the technique scored very well in a comparative test of different particle size analysis methods conducted with dust very similar to the one used in this study [32]. To make sure to measure unbiased samples, no dispersion (either mechanical or chemical) was applied during the analyses.

F. Other Instruments

Big Spring Number Eight (BSNE) dust collectors [38] were used to determine the airborne dust concentration in the wind tunnel during the experiments. The weight of the dust collected by the BSNEs and from the glass coupon was determined with a precision of 0.0001 g on an LA 214i analytical balance (VWR, Haasrode, Belgium).

G. Test Dust

Since soiling is particularly important in arid areas, and many solar plants have been installed, or are being planned, in desert regions, we opted for a dust that is typical for this type of environment. Dust prepared from Belgian Brabantian loess was used in the tests. Being a desert dust in origin, this dust, and especially its particle size composition, is very representative for almost all natural dusts that are currently found in the contemporary terrestrial deserts (see, for example, [39], [40]). It is also very similar to ISO 12103-1 A4 Coarse (ISO 5011 Coarse) standard dust. The mineralogical and sedimentological properties of the test dust are described in [41] and [42]. The median diameter of the dust used in the experiments was 32 μm. All dust was air-dry.

III. Experimental Setup and Procedure

To understand how PV modules affect the particle size characteristics of dust that accumulates on them, the following four factors were investigated: effect of wind speed, effect of tilt angle, variation of the particle size characteristics over the module, and effect of particle size on the dust accumulation pattern on the module. The procedure that was followed is described below.

The experimental glass plate, with the different strips marked on it, was installed in the wind tunnel at 600 cm from the entrance of the test section. No special arrangements were made in the test section upstream of the glass plate (empty fetch), and under these conditions the boundary layer in the wind tunnel's test section (at 600 cm from the inlet) was 12 cm thick. By installing the rotational axis of the glass plate at a height of 30 cm the glass plate remained outside the boundary layer for all tilt angles including vertical tilt. Four freestream wind velocities were tested: 1, 2, 3 and 4 m s^{-1}. The correct values as measured with the pitot tube were: 1.0 m s^{-1}, 2.0 m s^{-1}, 3.1 m s^{-1} and 4.1 m s^{-1}. A total of 13 tilt angles were investigated: 90 °, 75 °, 60 °, 45 °, 30 °, 15 °, 0 ° (horizontal position), -15 °, -30 °, -45 °, -60 °, -75 ° and -90 °. Positive values refer to forward tilt (sedimentation surface facing the wind); negative values refer to backward tilt. This resulted in a total of 52 combinations of wind speed and tilt angle. In addition to this, and to investigate the differences with the airborne dust, 4 extra experiments (one for each wind speed) were conducted in which the airborne dust that was transported at the same elevation as the rotational axis of the glass plate was collected. The total number of experiments was thus equal to 56. Airborne dust was collected with 3 test BSNEs, the first at the central axis of the glass plate and the two others at 10 cm from the central axis (one left, the other right) so that potential lateral variations in particle size over the 20-cm wide test strips could be detected and accounted for.

During each experiment, a total of 500 g dust was released in the wind tunnel. At the location where the glass plate was installed this corresponded to an airborne dust concentration of 0.25 g m^{-3}. Using such a concentration makes it possible to collect enough dust for a detailed particle size analysis with the Malvern Mastersizer instrument in a reasonable time, of the order of several minutes. To correct for potential differences in airborne dust concentration that could accidentally occur between tests, two reference BSNEs were installed at 600 cm fetch and 30 cm height (same as the glass plate), the first 20 cm left and the second 20 cm right from the lateral edges of the glass plate. By measuring the airborne concentration with these two correction samplers the accumulation on the glass plate can be recalculated to identical conditions of airborne dust concentration.

After each experiment the glass plate was taken from the wind tunnel and the dust accumulated on each of the five test strips was collected with a brush. Its weight was measured

using an analytical balance with a precision of 0.0001 g. The dust was then stored for subsequent particle size analysis. The dust collected by the BSNEs was also weighed (same precision) and stored.

Before each new test, the glass plate was carefully cleaned with a dry and clean cloth and the floor of the wind tunnel was also cleaned with a vacuum cleaner. This ensured identical start conditions for each experiment.

Particle size analysis of all 272 dust samples (260 samples collected from the test strips and 12 samples collected from the test BSNEs) was performed with the Malvern Mastersizer instrument. No dispersion was used during the analysis. The instrument measured a continuous particle size spectrum between 0.05 μm and 880 μm. Data can be displayed in any desired presentation; for this study we used 70 size classes of 2 μm wide, from <2 μm to 138-140 μm. There were no particles >140 μm.

Data can be analyzed for any particle size class desired. In this paper the median diameter (D50) has been used as a representative for the sample as a whole.

IV. Results

A. Effect of Wind Speed

To quantify the effect of wind on the particle size distribution of dust that accumulates on a PV module we first calculated the difference (in median diameter) between the airborne dust and the dust on the glass plate. In Fig. 2 that difference is displayed for all 13 tilt angles investigated. Data refer to the glass plate as a whole, in other words, all five test strips together. Several observations can be made. First, dust that accumulates on a PV module is finer than the airborne dust present at the same location. This is true for all backward tilt positions, and also for forward tilt provided the wind blows faster than 2 m s^{-1}. The difference can be large: values up to approximately 25 μm were measured. This is substantial taking into account that the median diameter of the original test dust was 32 μm. Secondly, with the exception of forward tilt up to 2 m s^{-1}, higher wind speeds result into finer dust on the glass plate. Third, the rate at which the dust becomes finer with increasing wind speed is larger for backward tilt than for forward tilt. Section V (Discussion) provides a physical explanation for these observations.

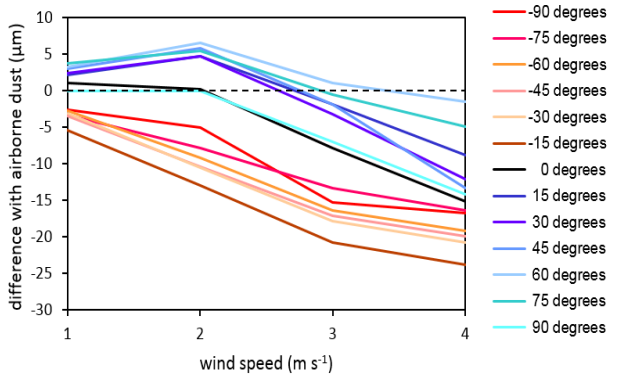

Fig. 2. Difference in median particle diameter between airborne dust and the dust that accumulated on the glass plate, as a function of wind speed.

B. Effect of Tilt Angle

The effect of tilt angle is displayed in Fig. 3. For backward tilt the difference with airborne dust (finer dust on the glass than in the air) is largest at an inclination of 15 °; the larger the tilt, the smaller the difference with the airborne dust becomes. The same is true for forward tilt, at least when the wind blows faster than 2 m s^{-1}, and up to a tilt angle of 60 °. The coarsening of the dust (coarser dust on the glass than in the air) that was already observed in Fig. 2 for wind speeds below 2 m s^{-1} and forward tilt is also apparent in Fig. 3; we refer to Section V for a physical explanation.

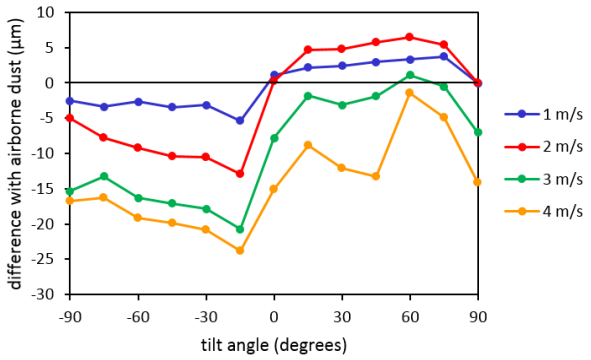

Fig. 3. Difference in median particle diameter between airborne dust and the dust that accumulated on the glass plate, as a function of tilt angle. Negative tilt angle refers to backward tilt; positive tilt angle refers to forward tilt.

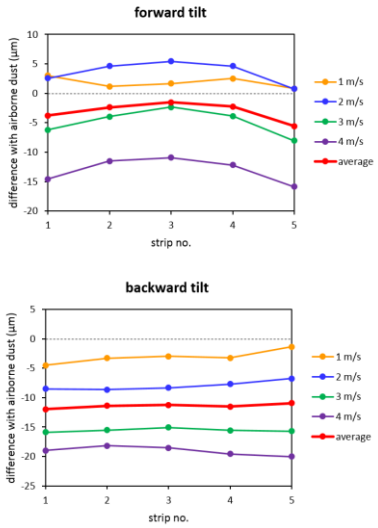

Fig. 4. Difference in median particle diameter between airborne dust and the dust that accumulated on the glass plate, for the five test strips on the glass. To allow direct comparisons between forward tilt and backward tilt the vertical axis spans the same particle size interval in the two figures. Airflow from left to right.

C. Variation of the Particle Size Characteristics over the Glass Plate

In Fig. 4 the difference (in median diameter) between the airborne dust and the dust on the glass plate has been plotted for the 5 experimental strips on the plate. Wind direction in the graphs is from left to right. The graphs show that there is a difference between forward and backward tilt. For forward tilt the tendency of the dust to become finer is most expressed near the leading end trailing edges of the glass plate. This is very clear for wind speeds of 2, 3 and 4 m s^{-1}; for the lowest wind speed (1 m s^{-1}) the trend is less consistent. For backward

tilt the pattern varied a little between wind speeds, but in general the tendency of the dust to become finer (compared to airborne dust) is fairly constant over the glass plate. We come back to this in Section V.

D. Effect of Particle Size on the Dust Accumulation Pattern on the Glass Plate

The wind tunnel data can be used to check whether the distribution of dust over the glass plate is uniform or non-uniform, and whether the distribution pattern is identical for all particle sizes or whether there are differences between particle size classes. Two examples are shown in Fig. 5. The upper graph on the left (30 °backward tilt, 4 m s^{-1}) shows that for this combination of tilt angle and wind speed, the finest particles (<20 μm) occur predominantly on the downwind located part of the glass plate whereas the coarsest particles (>30 μm) occur predominantly on the upwind located part. The intermediate particles (20-30 μm) are more uniformly distributed over the glass plate. The result is that the sediment as a whole becomes finer in the downwind direction (lower graph on the left in Fig. 5). In the second example (right in Fig. 5) most dust accumulated near the leading edge of the glass plate, and this was true for all particle size classes. Here too the dust became finer in the downwind direction (lower graph on the right). These examples show that the situation can differ from combination to combination: sometimes the accumulation pattern is similar for all particle size classes, sometimes it differs.

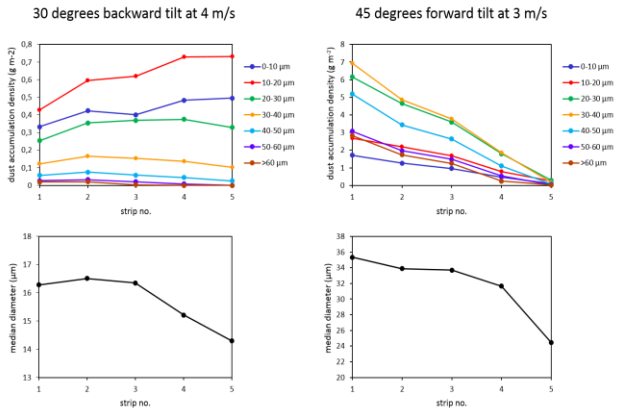

Fig. 5. Variation of dust accumulation over the glass plate for 7 particle size fractions (upper graphs) and variation of median particle diameter over the glass plate (lower graphs), for 2 test cases: 30 °backward tilt at 4 m s^{-1} and 45 °forward tilt at 3 m s^{-1}. Airflow from left to right.

V. Discussion

This section discusses why for backward tilt dust that accumulates on a PV module is finer compared to airborne dust, and why for forward tilt this is only the case for wind speeds above 2 m s^{-1}. A previous study [43] investigated how an obstacle in the airflow (in this case: a symmetrical hill oriented perpendicular to the wind) affects the particle size distribution of dust accumulating on the obstacle. It was found that on the backward tilted parts of the obstacle, the dust was considerably finer than the ambient dust (Fig. 6). The differences were substantial, up to 30 μm in median diameter, for a dust that was comparable to the dust used in the current study. The reason for the finer dust is the occurrence of a wake in the airflow pattern over the obstacle. In the current experiments flow separation will occur near the leading edge of the glass plate when the latter is tilted backward; the fine particles (which have a low mass and, therefore, a low response time) will show a higher probability to be sucked into the wake and deposit on the plate than the coarse particles, who have more inertia and will show a tendency to settle down more downwind. The result is a higher proportion of fine particles on the backward tilted surface than in the ambient air and a lower proportion of coarse particles; the combined effect is a finer dust on the surface than in the air.

In the case of forward tilt, slightly coarser dust can be expected on the surface compared to airborne dust (Fig. 6). This is what is seen at wind speeds of 1 and 2 m s^{-1} (Figs. 2 and 3). However, for forward tilted surfaces wind erosion will occur in the case of sufficiently high wind speeds. In the tests described in this study wind erosion did occur on the glass plate, but only for wind speeds over 2 m s^{-1}. This was verified by studying the accumulation patterns on the glass plate. Photos were made of the accumulation patterns, and the contrast was then increased to display better the internal structure of the dust layer. Two examples are shown in Fig. 7.

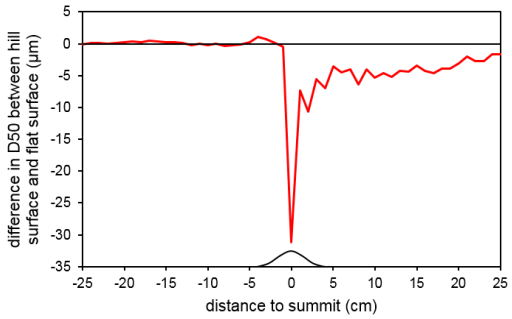

Fig. 6. Difference in median particle diameter between a curved hill surface and a flat horizontal surface. Data from [43].

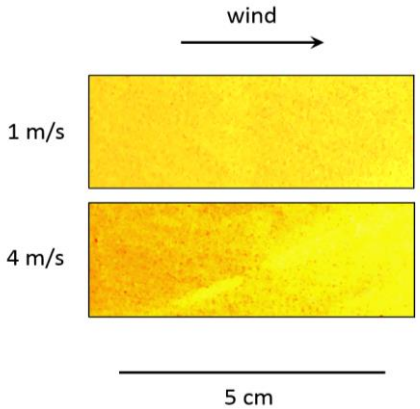

Fig. 7. Photos of the dust accumulation pattern on the glass plate. To make the spatial differences better visible the contrast has been increased. Red: much accumulation; yellow: little accumulation. Data are for a forward tilt angle of 30 °.

They are for a forward tilt of 30 °and wind speeds of 1 m s^{-1} and 4 m s^{-1}, respectively. The upper photo (at 1 m s^{-1}) shows a more or less uniform distribution of the dust on the glass; no apparent signs of wind erosion can be seen. The lower photo (at 4 m s^{-1}) shows a much more heterogeneous accumulation pattern, with clear erosion features on the right. The dust that was used in the experiments has a median

diameter of approximately 32 μm and more than 99.9% of the particles are smaller than 100 μm. For such sediment, the wind erosion threshold decreases as the particles become coarser (Fig. 8). This means that when wind erosion occurred on the glass plates in the tests, it are the coarsest particles that will be the most rapidly evacuated from the glass. The result is that the sediment that remains on the glass will become finer, and this is why at wind speeds above 2 m s^{-1} the dust on the forward tilted surfaces is finer than the airborne dust whereas for lower wind speeds it is slightly coarser.

In the case of forward tilt, wind erosion occurs preferentially near the leading and trailing edges of the glass plate because the airflow is most disturbed at these zones. The consequence is that, at forward tilt, the finest dust is also found in these zones (Fig. 4). When wind erosion is absent, such as for 1 m s^{-1}, the pattern may be different (Fig. 4). Note that the pattern at 2 m s^{-1} was still similar to the pattern at higher wind speeds (3 and 4 m s^{-1}); this could be an indication that some small wind erosion could still have occurred close to the leading and trailing edges. For backward tilt, no (or at least no important) wind erosion is expected to occur on the surface; the particle size distribution of the accumulated dust is fairly uniform (Fig. 4).

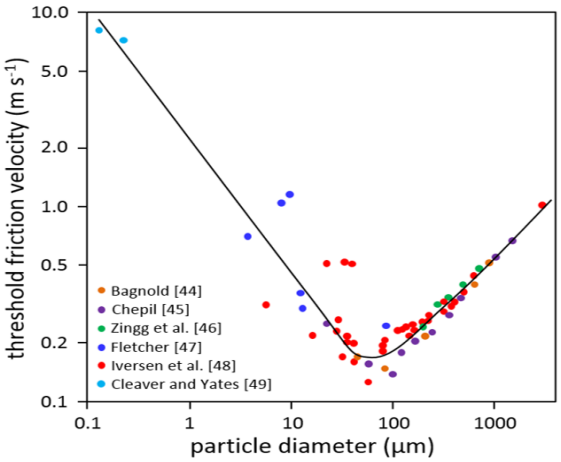

Fig. 8. Threshold friction velocity as a function of particle diameter.

A. Limitations and Future Research

This study investigated the effect of wind speed and tilt angle on the differences in particle size and particle size distribution that occur between airborne dust and dust accumulated on a glass surface, studied variations in particle size distribution that occur over the glass plate, and identified differences in the accumulation pattern between particle size classes. Other factors that may affect the particle size distribution but were not investigated in this study are:

- Effect of wind direction. Since the airflow field over a PV module changes with the orientation of the module in the wind it is likely that changes in the particle size distribution pattern additional to those described in this study will occur when wind direction changes.
- Effect of the module's size, orientation (portrait or landscape) and aspect ratio. These factors, in combination with wind speed and wind direction, affect the airflow field and therefore also the particle size distribution on the module.
- Multi-module panels. In multi-module panels the individual modules may touch each other or they may be separated by an air gap. Such air gaps, and their position and width, will affect the airflow over the panel and, therefore, the particle size distribution on the different modules.
- Lateral variations in particle size distribution. The current study investigated variations in particle size and particle size distribution along the module, in other words, parallel with the wind. Variations in particle size and particle size distribution in the lateral direction were not studied.

Future studies should be performed to investigate the effects and relevance of these factors.

VI. Conclusions

The wind tunnel tests show that dust that accumulates on PV surfaces is finer than the ambient airborne dust, except for a combination of forward tilt AND low wind velocity. For wind velocities large enough to initiate wind erosion the accumulated dust will be finer than the airborne dust even in the case of forward tilt. For backward tilt, wind erosion is less likely and under such circumstances the accumulated dust is always finer than the airborne dust. Reasons for the finer dust are the preferential accumulation of the finer particles in the wake of the inclined module due to their lower response time compared to coarse particles, and (in the case of wind erosion) the preferential removal of the coarsest fractions of the dust by the wind. The tests also showed that in the case of forward tilt, accumulated dust is finest near the leading and trailing edges of PV modules, which are the zones most vulnerable to wind erosion. For backward tilt the particle size distribution over a PV module is more uniform.

The pattern of dust accumulation over a PV module may vary according to the particle size class that is considered. Differences in such patterns may be considerable, or patterns may be similar for all particle sizes depending on the combination of wind speed and tilt angle.

This study shows that the particle size characteristics of dust that accumulates on a PV module are different compared to the particle size characteristics of the ambient airborne dust, and that the internal variations of the particle size distribution over a module can be substantial. These variations are important because in many PV modules the solar cells are connected in series. To minimize performance losses of the separate cells, the cells in the string thus need to be matched in current. However, the uneven soiling, and the differences in particle size distribution between the cells, will result in a reduction of the potential energy output. Theoretical and physical models that predict the energy production of a PV system should, therefore, incorporate these internal variations and the differences with airborne dust.

References

[1] 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, September 2014.

[2] F. Araya, P. Ferrada, J. Rabanal, A. Marzo, and E. Fuentealba, "Performance analysis of photovoltaics systems installed at different sites in the Atacama desert," in *Proc. 32nd European Photovoltaic Solar Energy Conference and Exhibition*, 2016, pp. 1635-1640.

[3] M. Piliougine, C. Cañete, R. Moreno, J. Carretero, J. Hirose, S. Ogawa, *et al.*, "Comparative analysis of energy produced by photovoltaic modules with anti-soiling coated surface in arid climates," *Appl. Energ.*, vol. 112, pp. 626-634, December 2013.

[4] E. Cabrera, A. Schneider, E. Wefringhaus, J. Rabanal, P. Ferrada, D. Thaller, *et al*., "Advancements in the development of 'ATAMO': A solar module adapted for the climate conditions of the Atacama desert in Chile - The impact of soiling and abrasion," in *Proc. 32nd European Photovoltaic Solar Energy Conference and Exhibition*, 2016, pp. 1573-1578.
[5] H. Hottel and B. Woertz, "The performance of flat plate solar heat collectors," *ASME Trans*., vol. 64, pp. 91-104, January 1942.
[6] R. Appels, B. Lefevre, B. Herteleer, H. Goverde, A. Beerten, R. Paesen, *et al.*, "Effect of soiling on photovoltaic modules," *Sol. Energy*, vol. 96, pp. 283-291, October 2013.
[7] S. C. S. Costa, A. S. A. C. Diniz, and L. L. Kazmerski, "Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012–2015," *Renew. Sustain. Energy Rev*., vol. 63, pp. 33-61, September 2016.
[8] A. Jonkers, "De invloed van stof en glastextuur op de performantie van zonnepanelen," M.Sc. thesis, KU Leuven, Leuven, Belgium, 2014.
[9] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renew. Sust. Energ. Rev*., vol. 14, pp. 3124-3131, December 2010.
[10] 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. Sust. Energ. Rev*., vol. 59, pp. 1307-1316, June 2016
[11] K. Menoufi, "Dust accumulation on the surface of photovoltaic panels: Introducing the photovoltaic soiling index (PVSI)," *Sustainability*, vol. 9, no. 6, June 2017.
[12] S. Ghazi, A. Sayigh, and K. Ip, "Dust effect on flat surfaces - A review paper," *Renew. Sust. Energ. Rev*., vol. 33, pp. 742-751, May 2014.
[13] S. A. M. Said and H. M. Walwil, "Fundamental studies on dust fouling effects on PV module performance," *Sol. Energy*, vol. 107, pp. 328-337, September 2014.
[14] 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. Sust. Energ. Rev.*, vol. 22, pp. 698-733, June 2013.
[15] F. M. Zaihidee, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, "Dust as an unalterable deteriorative factor affecting PV panel's efficiency: Why and how," *Renew. Sustain. Energy Rev*., vol. 65, pp. 1267-1278, November 2016.
[16] W. Javed, Y. Wubulikasimu, B. Figgis, and B. Guo, "Characterization of dust accumulated on photovoltaic panels in Doha, Qatar," *Sol. Energy*, vol. 142, pp. 123-135, January 2017.
[17] M. H. Bergin, R. Greenwald, J. Xu, Y. Berta, and W. L. Chameides, "Influence of aerosol dry deposition on photosynthetically active radiation available to plants: A case study in the Yangtze delta region of China," *Geophys. Res. Lett*., vol. 28, pp. 3605-3608, September 2001.
[18] H. Qasem, T. R. Betts, H. Müllejans, H. AlBusairi, and R. Gottschalg, "Dust-induced shading on photovoltaic modules," *Progr. Photovolt.: Res. Appl*., vol. 22, pp. 218-226, February 2014.
[19] S. A. Sulaiman, H. H. Hussain, N. S. H. N. Leh, and M. S. I. Razali, "Effects of dust on the performance of PV panels," *Int. J. Mech. Mechatron. Eng*., vol. 5, pp. 2028-2033, 2011.
[20] J. Tanesab, D. Parlevliet, J. Whale, T. Urmee, and T. Pryor, "The contribution of dust to performance degradation of PV modules in a temperate climate zone," *Sol. Energy*, vol. 120, pp. 147-157, October 2015.
[21] M. S. El-Shobokshy and F. M. Hussein, "Effect of dust with different physical properties on the performance of photovoltaic cells," *Sol. Energy*, vol. 51, pp. 505-511, December 1993.
[22] S. Pulipaka, F. Mani, and R. Kumar, "Modeling of soiled PV module with neural networks and regression using particle size composition," *Sol. Energy*, vol. 123, pp. 116-126, January 2016.
[23] H. Shi, R. Mohanty, S. Chakravarty, R. Cabiscol, M. Morgeneyer, H. Zetzener, *et al.*, "Effect of particle size and cohesion on powder yielding and flow," *KONA Powder Part. J*., January 2018.
[24] W. D. Kemper and R. C. Rosenau, "Soil cohesion as affected by time and water content," *Soil Sci. Soc. Am. J*., vol. 48, pp. 1001-1006, September-October 1984.
[25] M. A. Felicetti, F. Piantino, J. R. Coury, and M. L. Aquiar, "Influence of removal time and particle size on the particle substrate adhesion force," *Braz. J. Chem. Eng*., vol. 25, pp. 71-82, March 2008.
[26] H. R. Moutinho, B. To, C.-S. Jiang, C. Engtrakul, A. Einhorn, A. Sellinger, *et al*., "Effects of solar-glass coatings on the adhesion forces related to soiling," in *Proc. 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion*, 2018, pp. 3439-3443.
[27] X. Zheng, *Mechanics of Wind-Blown Sand Movements*, Dordrecht, the Netherlands: Springer Science & Business Media, 2009, p. 309.
[28] J. F. Kok, E. J. R. Parteli, T. L. Michaels, and D. B. Karam, "The physics of wind-blown sand and dust," *Rep. Prog. Phys*., vol. 75, p. 106901, October 2012.
[29] R. A. Zakhidov and A. Ismanzhanov, "Investigation of abrasive action of atmospheric particles on the reflectance of mirrors," *Appl. Sol. Energy*, vol. 16, pp. 43-47, January 1980.
[30] R. S. Anderson, "Eolian sediment transport as a stochastic process: The effects of a fluctuating wind on particle trajectories," *J. Geol*., vol. 95, pp. 497-512, July 1987.
[31] I. Nayshevsky, Q. F. Xu, and A. Lyons. (2018). Literature survey of dust particle dimensions on soiled solar panel modules. *Online Interactive Map*. [Online]. Available http://www.condensationexperiments.com/WorldBubbleMap/mymap
[32] D. Goossens, "Techniques to measure grain size distributions of loamy sediments: A comparative study of ten instruments for wet analysis," *Sedimentology*, vol. 55, pp. 65-96, February 2008.
[33] L. L. Kazmerski, A. S. A. C. Diniz, C. B. Maia, M. M. Viana, S. C. Costa, P. P. Brito, *et al*., "Fundamental studies of adhesion of dust to PV module surfaces: Chemical and physical relationships at the microscale," *IEEE J. Photovolt*., vol. 6, pp. 719-729, May 2016.
[34] C. Sansom, H. Almond, P. King, E. Endaya, and S. Bouaichaoui, "Airborne sand and dust soiling of solar collecting mirrors," in *Proc. AIP Conf*., 1850, p. 130011, June 2017.
[35] Y. Jiang, L. Lu, A. R. Ferro, and G. Ahmadi, "Analyzing wind cleaning process on the accumulated dust on solar photovoltaic (PV) modules on flat surfaces," *Sol. Energy*, vol. 159, pp. 1031-1036, January 2018.
[36] E. Kluggmann-Radziemska, "Degradation of electrical performance of a crystalline photovoltaic module due to dust deposition in northern Poland," *Renew. Energy*, vol. 78, pp. 418-426, June 2015.
[37] J. Sylvia, "Characterization of dust on solar devices in Southers Nevada," Ph.D. dissertation, UNLV, Las Vegas, NV, USA, 2017.
[38] D. W. Fryrear, "A field dust sampler," *J. Soil Water Conserv*., vol. 41, pp. 117-120, March-April 1986.
[39] T. L. Péwé, "Desert dust: Origin, characteristics, and effect on man," *Geol. Soc. Am.*, Special Paper, vol. 186, 1981.
[40] N. J. Middleton, "Desert dust hazards: A global review," *Aeolian Res*., vol. 24, pp. 53-63, February 2014.
[41] D. Goossens, "Wind tunnel protocol to study the effects of anti-soiling and anti-reflective coatings on deposition, removal, and accumulation of dust on photovoltaic surfaces and consequences for optical transmittance," *Sol. Energy*, vol. 163, pp. 131-139, March 2018.
[42] D. Goossens, R. Lundholm, H. Goverde, and J. Govaerts, *Effect of Soiling on Wind-Induced Cooling of Photovoltaic Modules and Consequences for Electrical Performance*.
[43] D. Goossens, "Aeolian deposition of dust over hills: The effect of dust grain size on the deposition pattern," *Earth Surf. Proc. Land*., vol. 31, pp. 762-776, May 2006.
[44] R. A. Bagnold, "The transport of sand by wind," *The Geogr. J*., vol. 89, pp. 409-438, May 1937.
[45] W. S. Chepil, "Dynamics of wind erosion. 2: Initiation of soil movement," *Soil Sci*., vol. 60, pp. 397-411, November 1945.
[46] A. W. Zingg, "Wind tunnel studies of the movement of sedimentary material," in *Proc. Fifth Hydraulic Conference. Studies in Engineering*, Bulletin, vol. 34, 1953, pp. 111-135.
[47] B. Fletcher, "Incipient motion of granular materials," *J. Phys. D Appl. Phys*., vol. 9, pp. 2471-2478, June 1976.
[48] J. D. Iversen, J. B. Pollack, R. Greeley, and B. R. White, "Saltation threshold on Mars: The effect of inter-particle force, surface roughness, and low atmospheric density," *Icarus*, vol. 29, pp. 318-383, November 1976.
[49] J. W. Cleaver and B. Yates, "Mechanism of detachment of colloidal particles from a fiat substrate in a turbulent flow," *J. Colloid Interface Sci*., vol. 44, pp. 464-474, September 1973.

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