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AEOLIAN DUST DEPOSITION ON PHOTOVOLTAIC SOLAR CELLS: THE EFFECTS OF WIND VELOCITY AND AIRBORNE DUST CONCENTRATION ON CELL PERFORMANCE

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Abstract—Wind tunnel experiments were conducted to investigate the effect of wind velocity and airborne dust concentration on the drop of photovoltaic (PV) cell performance caused by dust accumulation on such cells. Performance drop was investigated at four wind velocities and four dust concentrations. *I–V* characteristics were determined for various intensities of cell pollution. The evolutions of the short circuit current, the open circuit voltage, the maximum power, the reduction of solar intensity received by the cells, and the fill factor variation with increasing cell pollution were examined. The deposition (and accumulation) of fine aeolian dust on PV cells significantly affects the performance of such cells. Wind velocity has an important impact on cell performance drop, since the drop is larger in high winds than in low winds. However, the wind also affects the sedimentological structure of the dust coating on the cell, resulting in a higher transmittance (of light) for coatings created during high winds. The wind tunnel experiments indicate that the former effect is more important than the latter, which means that, in general, the drop in PV cell performance due to dust accumulation is larger as wind speed increases. Airborne dust concentration also affects the drop in PV cell performance, since high dust concentrations lead to a higher accumulation on the cell. Contrary to wind speed, airborne dust concentration does not seem to affect the sedimentological structure of dust coatings (with respect to light transmittance) on PV cells. © 1999 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

During the last few years, there has been an increasing interest in the natural degradation processes that occur on solar collectors mounted outdoors. Many freshly installed collectors already show a reduction in their electric (or thermal) performance after a few weeks of operation (see Grassi (1985) for some examples). Since the losses continuously increase in the course of time, collector efficiency may drop to very low values after only a few years. Many collectors are designed to remain operational for periods of 20 years and more; hence the study of the natural degradation of solar cells is of particular importance.

According to Bethea et al. (1983), the primary sources of solar collector degradation are: hail, chemical weathering processes, radiative weathering, and contamination with airborne particulates, either of natural (soil) or industrial (carbon, soot, other dirt) origin. This paper focuses on the contamination with natural soil dust. According to Thomas et al. (1985), this may be considered the principal source of degradation of collectors mounted outdoors. Apart from diminishing the reflectance of mirrors and the transmittance of cell glazing, the presence of airborne particles may further affect the malfunctioning of solar collectors in different ways. The entry of very fine dust inside the electronic sun sensor window of a collector array may, for example, cause the array to loose track of the sun, as has been reported by Khoshaim et al. (1983) for a PV plant in Saudi Arabia. Also, airborne particles in the atmosphere affect the amount and properties of the radiation finally reaching the collectors (see Santamouris, 1991 and Abdelrahman et al., 1988), but this topic is outside the scope of this paper.

The pollution of solar cell surfaces by airborne particles has been recognized since the early 1960s (Dietz, 1963). The oldest studies mainly

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deal with thermal collectors, and more specifically with the effect dust accumulation exerts on mirror reflectance. The majority of these studies discuss reflectance measurements executed on outdoor mirrors (Roth and Pettit, 1980; Pettit and Freese, 1980; Roth and Anaya, 1980; Bethea et al., 1981; Deffenbaugh et al., 1986). Several authors also tried to simulate the deposition of dust on mirrors in the laboratory, i.e. under more controlled conditions, and investigated its effect on mirror reflectance (Young, 1976; Roth and Pettit, 1980; Bethea et al., 1983). Studies dealing with the effect of dust deposition on the transparency of cell glazing are more recent and mainly date from the early nineties. Outdoor measurements on glazing transparency have been performed by Nahar and Gupta (1990), El-Nashar (1994) and Bonvin (1995). Laboratory simulations were reported by Hasan and Sayigh (1992) and El-Shobokshy and Hussein (1993). Feuermann and Zemel (1993), in a similar approach, measured the degradation in pyranometer sensitivity due to dust accumulation on the pyranometer glass.

The influence of collector design on the amount and distribution of airborne dust on a collector was investigated by Goossens et al. (1993) and Smits and Goossens (1995). Both studies illustrated the need for a careful construction to avoid large accumulation on the collector surfaces.

Most studies dealing with the effect of dust accumulation on the electric performance of PV cells date from the last few years, although several outdoor measurements had been conducted 15 years ago (Khoshaim et al., 1984; Al-Busairi and Al-Kandari, 1987). The drop in short circuit current due to dust accumulation has been measured by Khoshaim et al. (1984), Pande (1992), Khoshaim et al. (1983) and Pande and Hill (1995) on outdoor cells and by Katzan and Stidham (1991) and El-Shobokshy and Hussein (1993) during laboratory experiments. Khoshaim et al. (1984) and Katzan and Stidham (1991) also report on the I–V characteristics of the cells. Measurements of open circuit voltage were performed by Pande (1992) and Hasan and Sayigh (1992). Maximum power output was investigated by Al-Busairi and Al-Kandari (1987) and Hasan and Sayigh (1992) on outdoor cells and by Katzan and Stidham (1991) and El-Shobokshy and Hussein (1993) in laboratory experiments. In all these studies, the negative effect of dust accumulation on PV cell performance was remarkable. Also Rolland et al. (1990) mentioned the negative effect of dust accumulation on PV cell performance.

Probably the most complete study conducted thus far is that by El-Shobokshy and Hussein (1993). In the laboratory, they polluted PV surfaces with different kinds of dust and measured the electric output of the cells under different conditions. The parameters investigated were: the short circuit current, the maximum power, the reduction in solar intensity received by the PV cells, and the fill factor. The effect of particle size was investigated using five size fractions ranging from 5 to 80 μm. In addition, three kinds of dust (limestone, cement and carbon) were tested. Both parameters significantly affected the reduction of PV cell performance.

Although very useful, the work executed by El-Shobokshy and Hussein (1993) contains some important restrictions. Probably the most important of these is that all the PV surfaces they prepared were polluted under zero-wind conditions. In natural circumstances there is always some movement of the air, even in very calm, apparently windless conditions, due to turbulence or to natural convection or advection. Since the response time of small dust particulates is extremely low, fine particle transport will occur even at very low wind speeds. On the other hand, dust pollution of PV cells mounted in deserts typically occurs during high wind speeds, for example during dust storms, when large amounts of sediment are eroded from the ground and the concentration of particles in the atmosphere is very high. Long-term measurements of dust deposition in the Negev desert have shown that the largest deposition always occurs during high wind speeds (Goossens and Offer, 1995). In addition, the ‘background’ wind speed (excluding the unusual storm events) is typically of the order of 1–3 $\mathrm{m\,s^{-1}}$ (Offer and Goossens, 1990), i.e. significantly different from zero. Since even low winds significantly affect the sedimentological structure of dust coatings on flat surfaces (Goossens, 1991), the zero-wind approach by El-Shobokshy and Hussein (1993) is an oversimplification of the real process.

Another restriction of El-Shobokshy and Hussein’s work is that no natural desert dust was used in their experiments. The limestone, cement and carbon dust they used is of great significance for cell pollution in urban or industrial areas, but in many desert plants the pollution by natural soil dust is much more important. Finally, El-Shobokshy and Hussein’s work only deals with the effect of particle properties.

In this study, natural soil dust is used as a pollutant. We also add a meteorological component to the topic and investigate the effect wind speed and airborne dust concentration exert on PV cell performance. Attention will also be paid to the sedimentological structure of the dust coating on the PV glazing and to the effect it exerts on cell performance. The aim of the study is, therefore, twofold: we intend to study both the aerodynamic and the sedimentological effect that wind speed and airborne dust concentration exert on PV cell performance.

2. EXPERIMENTAL FACILITIES

The dust experiments were conducted in the aeolian dust wind tunnel of the Laboratory for Experimental Geomorphology, Katholieke Universiteit Leuven, Belgium. The tunnel is of the closed-return type and contains two test sections. All experiments were carried out in the large section, which is 7.6 m long, 1.2 m wide and 0.6 m high.

Dust transport in the tunnel was generated by means of an Engelhardt laboratory dust-cloud producer which was connected to the tunnel. This apparatus ensures a continuous feed to the air current of natural dust particles, and allows the operator to adjust dust discharge.

A more detailed description of the wind tunnel and the dust-cloud producer can be found in Goossens and Offer (1988).

Wind velocities were measured with a standard Pitot tube and a digital Furness FC016 manometer with an accuracy of 0.001 mm water pressure. Dust amount on the PV cell was determined using a Mettler PJ3000 balance with an accuracy of 0.001 g.

The PV cell used in the experiments was a standard multicrystalline silicon cell with a rather low efficiency. It was covered with a titaniumoxide anti-reflective layer and was encapsulated in the following succession: glass–EVA–cell–EVA–trilaminate (tedlar–polyester–tedlar). It was chosen because of its high temporal stability and had a size of 10 cm × 10 cm. The glass type and finish are the same as for a standard production PV module. The spectral response of the cell ranges from 340 nm to 1180 nm (approximately), with a maximum sensitivity near 800 nm.

Measurements carried out under standard conditions showed a cell efficiency of approximately 11.5%. At 1 solar equivalent (1000 $\mathrm{W\,m^{-2}}$, spectrum AM1.5) the current density was 29.7 $\mathrm{mA\,cm^{-2}}$. During the wind tunnel experiments, no standard solar simulator was available, but an alternative was found in two halogen lamps of 1000 W and 500 W. These were fixed to a metal rail 70 cm above the PV cell. Special care was taken to avoid any shadowing (direct or indirect) on the cell. The 1000 W lamp contained a self-cooling device, keeping the emission of heat to a minimum. Due to the slightly different spectrum of the halogen lamps compared to the standard solar simulator, lower current densities were measured during the wind tunnel tests. This is not a problem provided the results are expressed in a relative (not in an absolute) form.

The *I*–*V* characteristics of the cell were measured using a Hameg HM203$_{-5}$ oscilloscope. This made it possible to determine the *I*–*V* characteristics in a very short time interval (a few seconds), avoiding a warming-up of the cell surface. Temperature of the cell surface was always around 25°C.

Light intensity of the solar simulator was measured with an Ophir Nova Laser Power–Energy Monitor. The measuring range of the instrument is from 300 nm to 1100 nm, which is almost exactly the spectral response interval of the PV cell used.

3. MATERIALS, METHODS AND PROCEDURE

All experiments were executed with natural aeolian dust prepared from Belgian Brabantian loess. The loess was dried, ground and sieved through a 63 μm sieve to exclude all sand particles. In the sifting, some of the finest particles were lost in small dust clouds. The remaining sediment consisted of 95% silt (2–63 μm) and 5% clay (<2 μm). It had a median diameter of 30 μm, which corresponds closely to the size of dust particles that settle on the earth's surface during natural dust storms (Yaalon and Ganor, 1979). Only 1% of the particles was coarser than 50 μm. As can be seen in Fig. 1, the dust was very well sorted.

Before each wind tunnel experiment, the PV cell was carefully cleaned with a soft cloth and the *I*–*V* characteristics of the clean cell were determined using the oscilloscope method described by Chenming and White (1983). No decrease was observed in the performance of the clean cell in the course of the experimental programme. The cell was then put into the wind tunnel. A 6 m empty fetch was used to allow the wind (and the dust) to reach equilibrium conditions before arriving at the PV cell. To avoid local aerodynamic disturbances, the wind tunnel floor surrounding the cell was carefully adjusted so that no roughness changes occurred near the

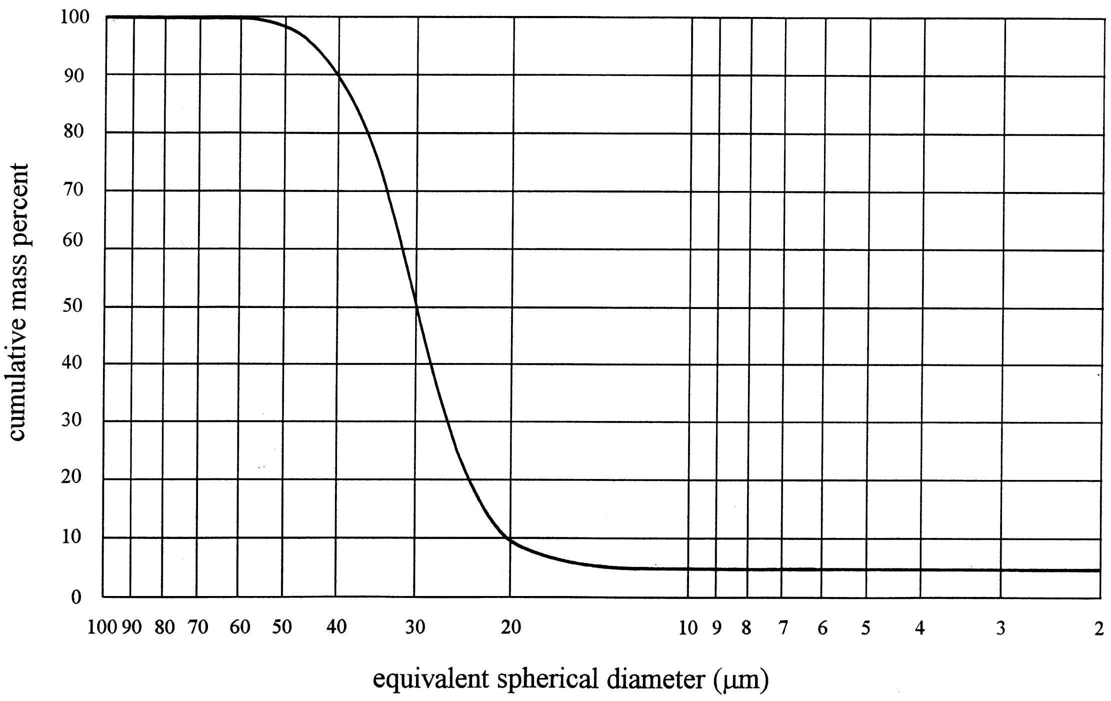

Fig. 1. Grain-size distribution of the dust used in the experiments.

cell's borders. The cell was always installed in a horizontal position.

Vertical wind velocity profiles were measured near the cell, at a fetch of 6 m. Four wind conditions were selected, with freestream velocities varying between 0.63 m s^{-1} and 2.59 m s^{-1}, corresponding closely to the average background speeds recorded at most desert stations (Offer and Goossens, 1990).

Seven wind tunnel experiments were performed. In the experiments 1, 2, 3 and 4, dust discharge of the dust-cloud producer was kept constant and equal to 20 kg h^{-1}. This corresponded to a dust concentration of about 2.25 g m^{-3}, at 5 cm above the PV cell surface. Table 1 shows the value of the freestream wind speed u_f and the friction velocity $u*$ during these four experiments. In the experiments 5, 6 and 7, wind speed was kept constant at 1.86 m s^{-1}, but dust discharge was set to 15 kg h^{-1}, 10 kg h^{-1} and 5 kg h^{-1}, corresponding to an air dust concentration (at 5 cm above the cell surface) of 1.69 g m^{-3}, 1.13 g m^{-3} and 0.56 g m^{-3}, respectively. Thus, four experiments are available to study the effect of wind velocity (at constant air dust concentration), and another four experiments can be used to study the effect of air dust concentration (at constant wind velocity).

Table 1. Freestream wind velocity, friction velocity, dust discharge and approximative dust concentration (at 5 cm above the cell surface) for the seven experiments

Exp. no.	Freestream wind velocity (m s^{-1})	Friction velocity (cm s^{-1})	Dust discharge (kg h^{-1})	Dust concentration (g m^{-3})
1	0.63	3.87	20	2.25
2	1.37	4.29	20	2.25
3	1.86	7.90	20	2.25
4	2.59	9.64	20	2.25
5	1.86	7.90	15	1.69
6	1.86	7.90	10	1.13
7	1.86	7.90	5	0.56

To investigate the gradual pollution of the PV cell throughout the experiments, each experiment was regularly interrupted to measure the amount of dust accumulated on the cell and to determine the cell's *I–V* characteristics. Extreme care was taken while transporting the cell from the wind tunnel to the solar simulator and vice versa to avoid any disturbance of the structure of the dust layer on the cell. The number of interruptions varied from experiment to experiment, but was always between 10 and 13. The duration of each run varied between 1 and 9 min, depending on wind velocity and dust concentration. After each run, the cell in the tunnel was immediately covered by a shelter to avoid uncontrolled dust deposition after the motor had been switched off.

After the dust experiments were accomplished, the *I–V* characteristics of the clean PV cell were determined for various solar (light) intensities. A variable resistor was used for this purpose. The

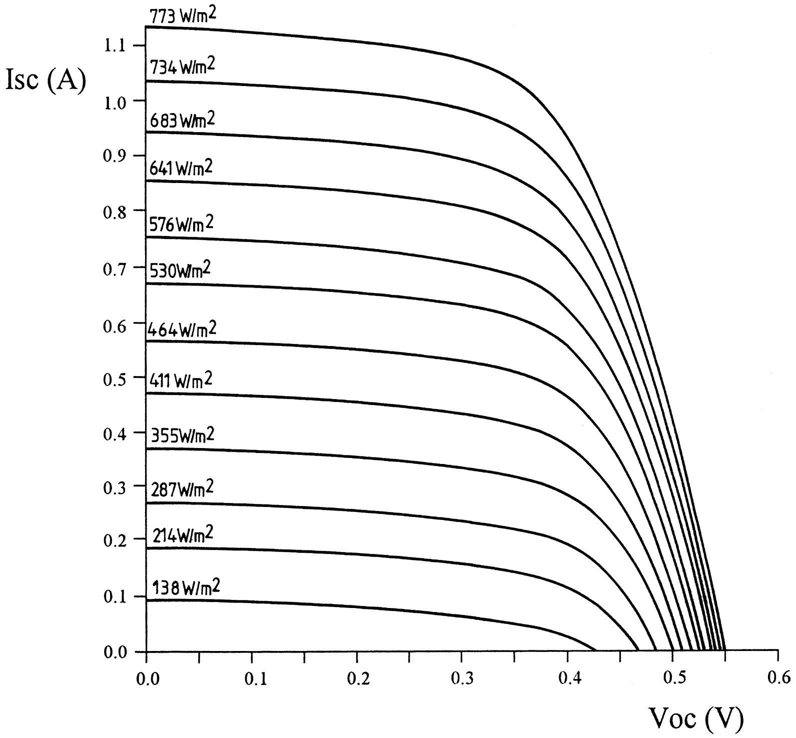

Fig. 2. *I–V* characteristics, at varying solar intensity, for the clean PV cell used in the experiments.

correct value of the light intensity was measured with the Ophir Nova Power Monitor.

From the *I–V* curves the following parameters were calculated: the short circuit current I_{sc}, the open circuit voltage V_{oc}, the maximum power $P_{max} = (I_{sc} \times V_{oc})_{max}$, the reduction R in solar intensity received by the PV cell, and the fill factor *FF*. The reduction in solar intensity was determined by locating each *I–V* curve on Fig. 2 and reading the value of solar intensity corresponding to the location of such a curve on Fig. 2. The difference between the value 773 W m^{-2} and the corresponding value in Fig. 2 gives a reasonable estimate for the reduction in solar intensity due to the difference in accumulation (El-Shobokshy and Hussein, 1993).

4. EXPERIMENTAL RESULTS

In this section we stick to a strict description of the wind tunnel results. Physical explanations and interpretations are discussed in Section 5.

The *I–V* characteristics of the clean PV cell at varying solar intensity are shown in Fig. 2. Fig. 3 shows the normalized short circuit current as a function of the normalized solar intensity. Reference values were the short circuit current at the maximum intensity used in the experiments (1138 mA) and the maximum intensity of 773 W m^{-2}. The relationship is not perfectly linear, especially at normalized solar intensities of 0.5 or less, probably because of the rather poor performance of the cell itself. A similar non-linear trend was observed by El-Shobokshy and Hussein (1993) during their experiments with limestone, cement and carbon dust.

4.1. Effect of wind velocity

Fig. 4 shows the effect of wind velocity on PV cell performance. On the left [Figs. 4(A1) to 4(E1)], the evolutions of I_{sc}, V_{oc}, P_{max}, R and *FF* are displayed as a function of the sedimentation time. On the right [Figs. 4(A2) to (E2)], the evolution of the same parameters is displayed as a function of the amount of dust that had accumulated on the cell surface (expressed in mg cm^{-2}). The distinction between both types of presentation is quite fundamental. Figs. 4(A1) to (E1) show how the drop in PV cell performance (due to dust accumulation) evolves, for different wind velocities, as a function of time, i.e. they display the aerodynamic effect the wind exerts on cell performance drop. This way of presentation refers to a situation where the same PV cell is polluted by dust during different storms, each characterized by a different wind velocity. In Fig. 4(A1), for example, it can be observed that, after a high wind velocity storm of a given duration, the drop

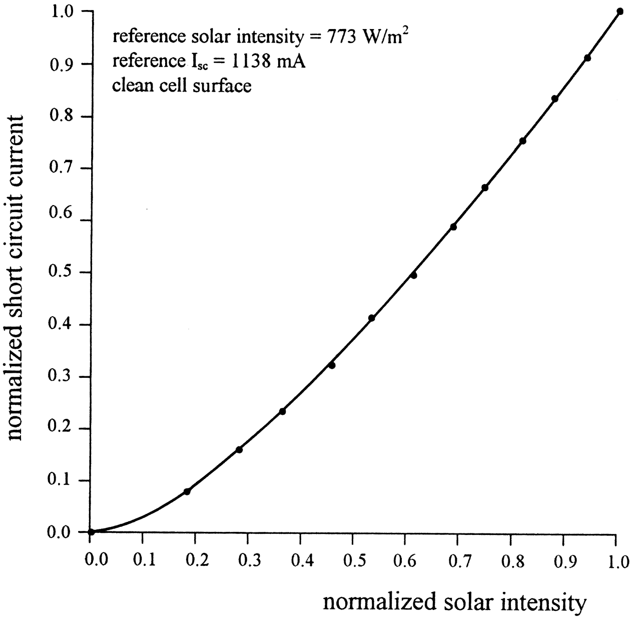

Fig. 3. Normalized short circuit current as a function of normalized solar intensity.

in I_{sc} is larger than after a storm of the same duration but with a smaller wind velocity. The right-hand figures, on the other hand, show how the drop in PV cell performance (due to dust accumulation) evolves, for different wind velocities, as a function of accumulation density on the cell surface, i.e. they display the sedimentological effect the wind exerts on cell performance drop. This way of presentation refers to a situation where PV cells are polluted with the same amount of dust, but at different wind velocities. Since the micromorphological characteristics of the dust coating on a cell depend, among other factors, on the velocity of the wind at which the coating has been created, the light transmittance of coatings created during high winds may differ from that of coatings created during low winds although the amount of dust on the cell is identical in both cases.

Figs. 4(A1)–(E1) show that the aerodynamic effect of the wind on cell performance drop is considerable. The degradation due to dust accumulation increases with wind speed for all parameters investigated, except for the fill factor *FF*, where no systematic variation is observed, at least not in the 10 min interval shown in the figure. Extending the accumulation time by several minutes leads to a systematic trend, however, with low fill factors at high wind velocities and high fill factors at low wind velocities.

Figs. 4(A2)–(E2) show that the sedimentological effect of the wind on cell performance drop is small, but systematic. The lower the wind, the higher is the drop in PV cell performance due to dust accumulation. There are some local disturbances in this trend in the V_{oc} and *FF* diagrams, but the general picture is clear. Apparently, light transmission in dust coatings created in low winds is smaller than transmission in coatings created in high winds.

4.2. Effect of airborne dust concentration

The effect airborne dust concentration exerts on PV cell performance is shown in Fig. 5. Similar to the wind velocity diagrams (Fig. 4), results are presented as a function of dust accumulation time (left in the figure) and the amount of accumulation on the cell surface (right in the figure).

Figs. 5(A1)–(E1) show that the aerodynamic effect of airborne dust concentration on PV cell performance drop is considerable. As could be expected, heavily polluted air (high dust concentrations) leads, in a same time interval, to a larger cell degradation than less polluted air (small dust concentrations). The trend is systematic in all diagrams, except in Fig. 5(E1), where the pattern becomes complex after an accumulation time of 7 min.

Figs. 5(A2)–(E2) indicate no systematic sedimentological effect of airborne dust concentration on cell performance drop, except perhaps for the open circuit voltage [Fig. 5(B2)], where small dust concentrations appear to result in larger performance drops. In general, airborne dust concentration does not seem to influence light transmittance in dust coatings on PV cells.

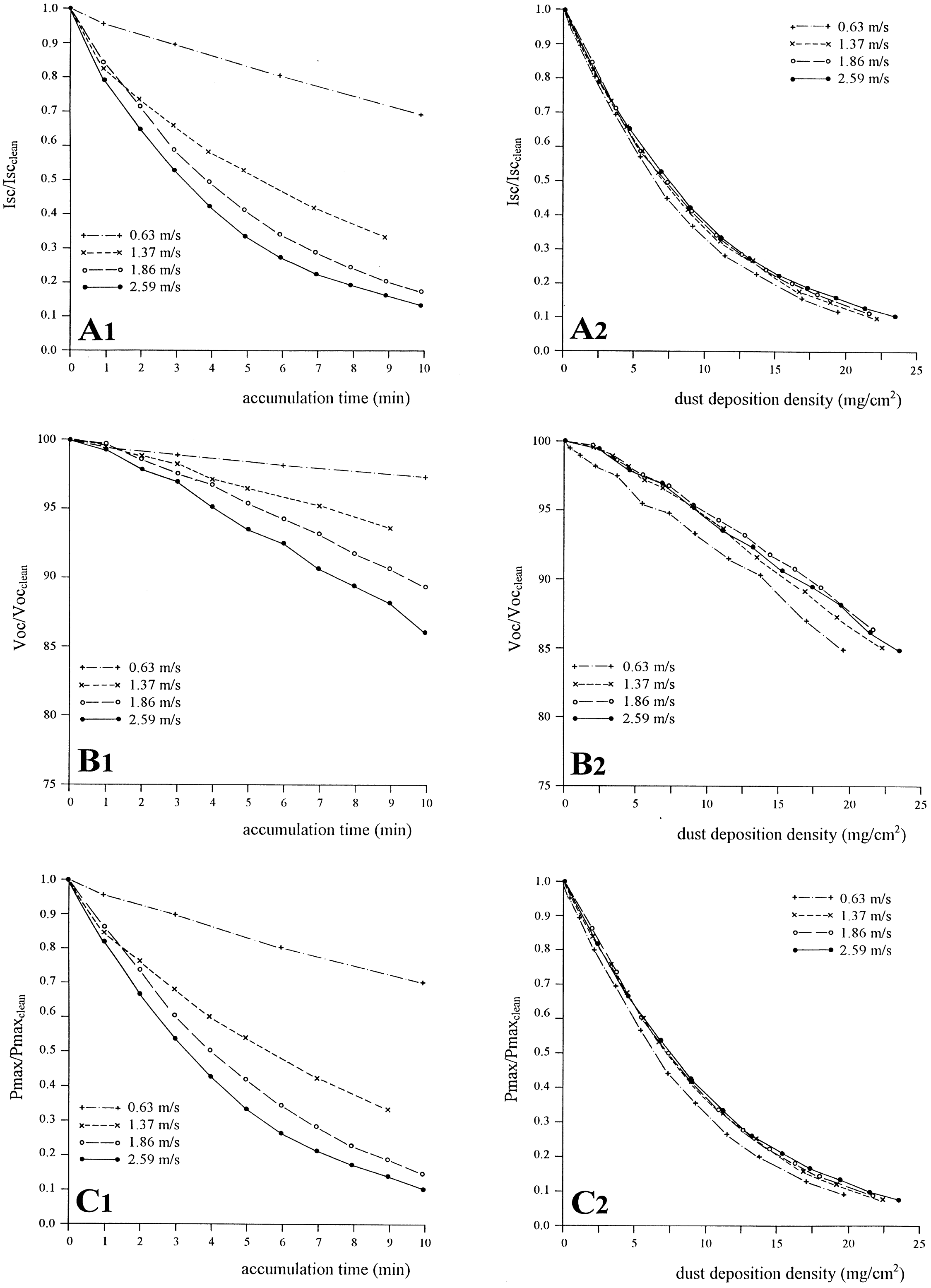

Fig. 4. Variations of: (A) short circuit current; (B) open circuit voltage; (C) maximum power output; (D) percentage reduction *R* in solar intensity received by the PV cell; and (E) fill factor with dust accumulation time (left) and dust accumulation quantity (right), for different values of wind velocity.

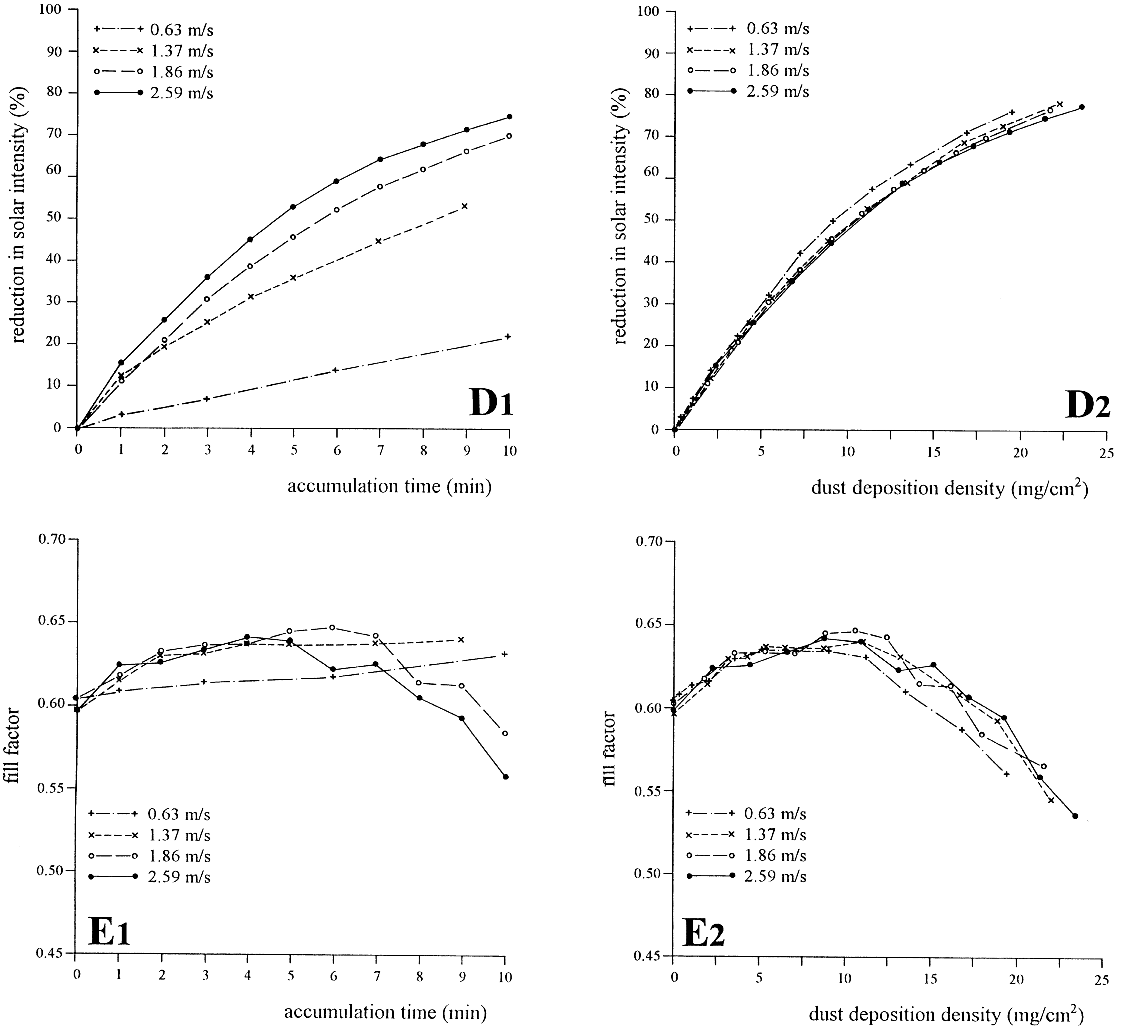

Fig. 4. (*continued*)

5. PHYSICAL EXPLANATION AND DISCUSSION

The experiments indicate a significant aerodynamic effect (for wind velocity as well as for airborne dust concentration), and, for the wind, a less important (but systematic) sedimentological effect on PV cell performance. We will now try to explain these effects.

5.1. The aerodynamic effect

The drop in PV cell performance is directly caused by the accumulation of the dust on the cell surface. To understand (and quantify) the accumulation, it suffices to understand (and quantify) dust deposition, for PV surfaces are always extremely smooth (usually made of glass). On very smooth surfaces, adhesion forces between dust particles and the surface are extremely large (Katzan and Stidham, 1991), and even very high wind velocities (up to 100 km h^{-1} and more) may be unable to erode fine particles from such surfaces (Bagnold, 1941).

The sedimentation flux F_S of fine dust can be quantified by means of the expression $F_S = v_d C$, where v_d is the velocity of deposition and C is the airborne dust concentration. At constant dust concentration, F_S (and also the sedimentation, S) is completely determined by v_d. The velocity of deposition depends on the type of dust, the characteristics of the sedimentation surface, and the aerodynamic properties of the air current (usually represented by the friction velocity, $u*$). For a given type of dust (Belgian Brabantian loess in our case) and a given sedimentation surface (the glass plate of our PV cell), S is, at any given value of C, completely determined by $u*$. Since $S \sim F_S$, $F_S \sim v_d$, $v_d \sim u*$ (Chamberlain, 1967) and $u* \sim u_f$, it follows that the sedimentation S on the PV cell is directly proportional to the freestream wind velocity u_f. Previous experiments executed by the first author showed that, for Belgian

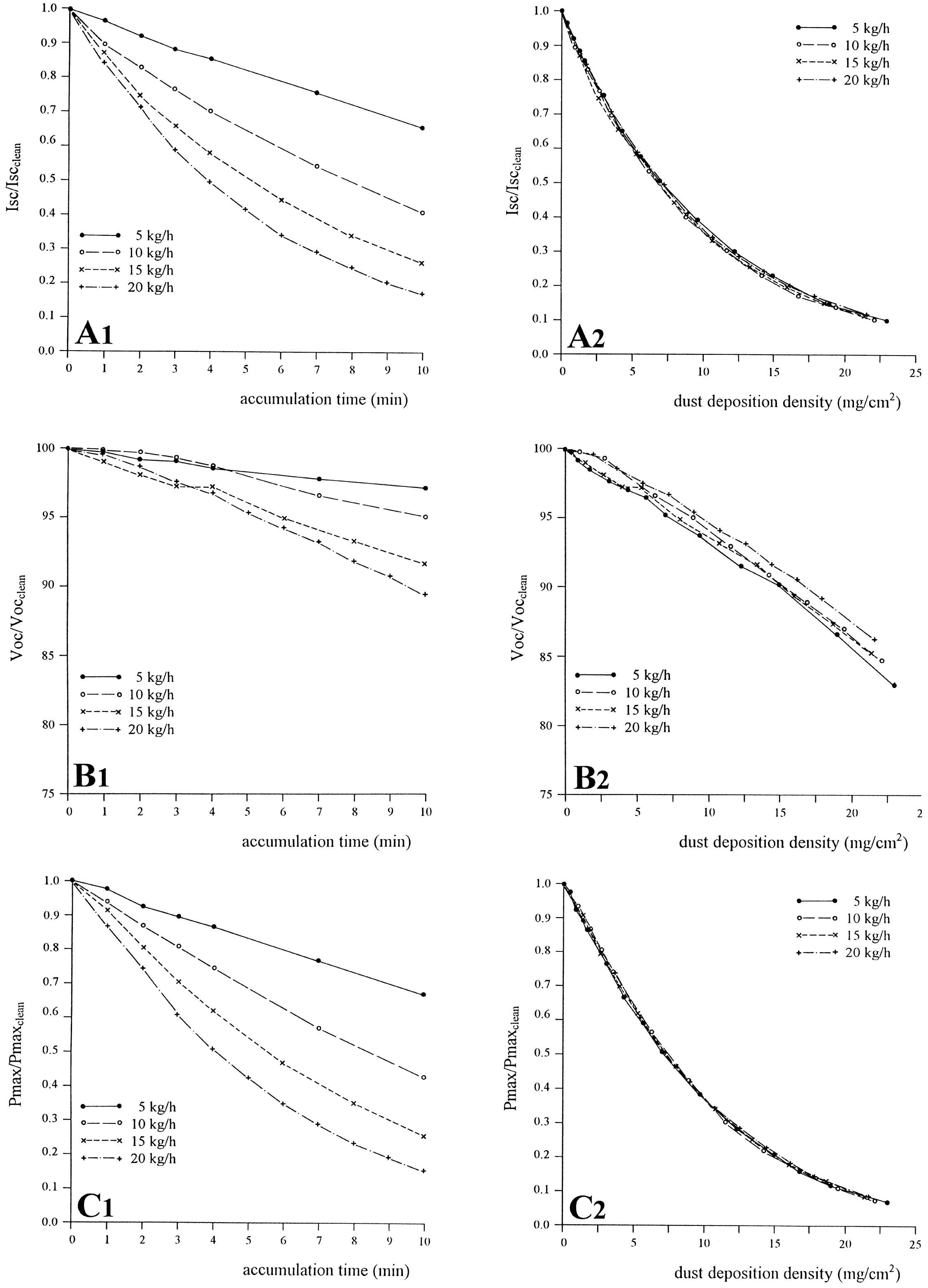

Fig. 5. Variations of: (A) short circuit current; (B) open circuit voltage; (C) maximum power output; (D) percentage reduction *R* in solar intensity received by the PV cell; and (E) fill factor with dust accumulation time (left) and dust accumulation quantity (right), for different values of airborne dust concentration.

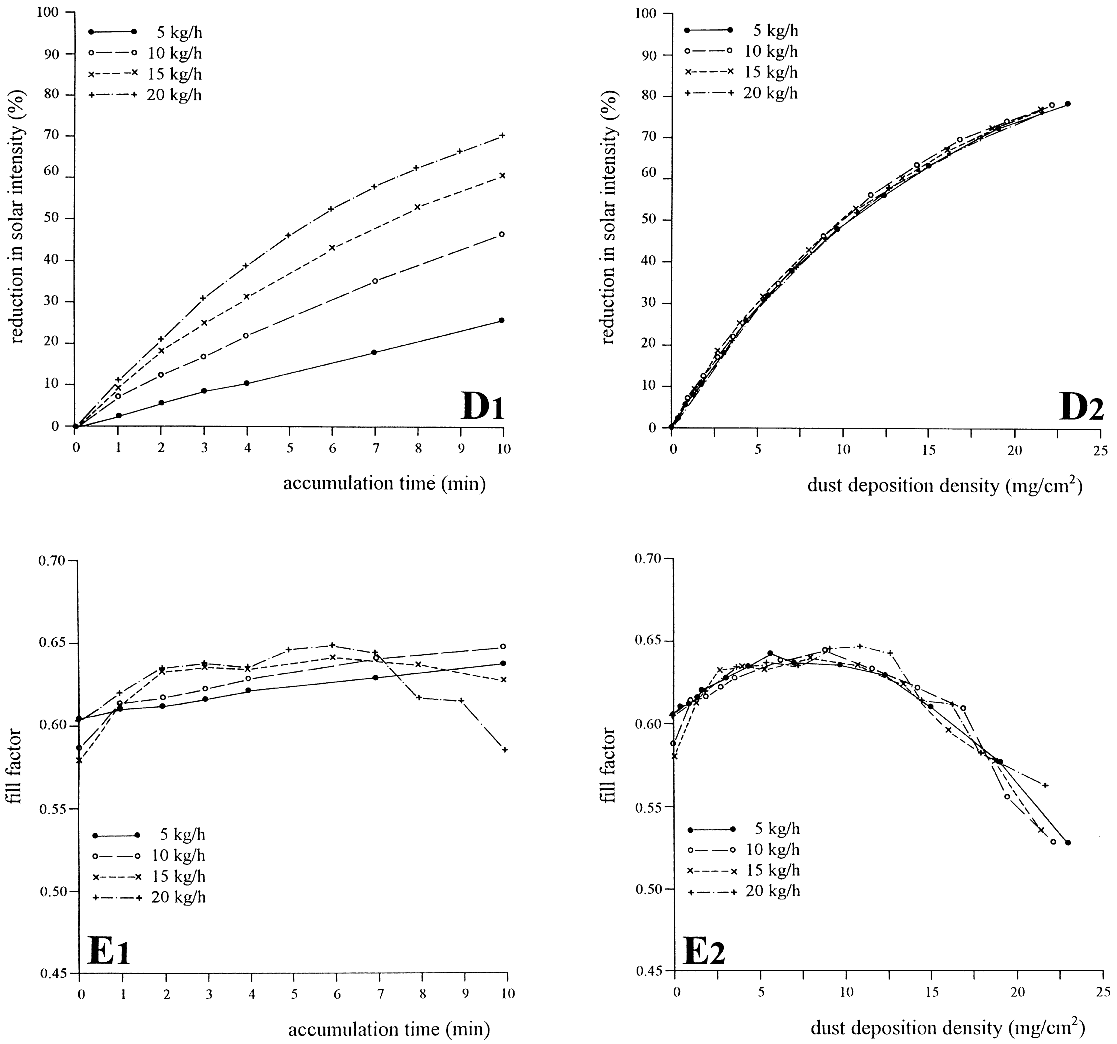

Fig. 5. (*continued*)

Brabantian loess, the relationship between S and u_f is even linear (Goossens, 1994a; Goossens, 1994b). This relationship explains the drop in PV cell performance with increasing wind velocity (at constant dust concentration).

5.2. The sedimentological effect

Why are dust coatings created in low winds less transparent than dust coatings created in high winds?

A few years ago, the first author investigated the morphometric and dynamic properties of dust coatings created by winds blowing over flat surfaces (Goossens, 1991). Very high resolution (1 μm) scans of the microtopography of such coatings were executed, and this at different wind velocities. It was found that, even if the sedimentation surface is extremely smooth (such as PV glazing), sedimentation does not occur homogeneously. The dust on the surface shows a typical (and regular) pattern of local accumulation bodies, which initially occur as isolated microhills but rapidly merge to form transverse microripples. These microripples were investigated in great detail in the study mentioned above. Three conclusions from this study are significant with respect to the PV experiments reported here:

1. Ripple spacing (defined as the distance between the crests of two adjacent ripples) increases with increasing wind velocity;
2. Ripple height (defined as the mean elevation of a ripple crest above the adjacent troughs) decreases with increasing wind velocity, provided wind is not too low;
3. The older the dust coating on the surface (i.e. the longer the sedimentation time), the higher its morphological homogeneity becomes (regular ripples of the same size and orientation, no open areas between the ripples).

Table 2 shows, for the four wind speeds simulated, spacing (λ) and height (h) of the microripples that developed on top of the dust coating on the PV cell, at a dust density (on the cell) of 20 mg cm^{-2}. The increase of spacing and the decrease of height with the wind is prominent.

The three factors mentioned above directly determine the spatial heterogeneity of the dust coating on the PV cell, and the degree of transparency of the coating for incident light. At large ripple heights, much of the cell surface is covered by a rather thick dust layer, resulting in a smaller transparency for the dust coating as a whole. Although the thinner dust zones in between the ripple bodies allow more light to penetrate to the cell, it is unclear whether this is sufficient to compensate for the decreased transparency in the ripples. Ripple spacing also plays a role. At large spacings the area in between the ripples is large, thereby offering more space where the dust coating is thin and light can easily penetrate to the cell. But the last factor, the stage of development of the ripple field, is the most important. In the study of Goossens (1991), it was found that dust ripple fields are, in their early stages of development, quite heterogeneous, with very short individual ripples and plenty of (empty, almost dust-free) space between the developing ripples. With increasing sedimentation time, ripple fields become more and more mature, many individual short ripples merge to form long macroripples, and, very important, the empty spaces between the ripples disappear. This means that the PV surface now becomes covered by a continuous dust coating, without open areas where the light can easily penetrate to the cell. Table 2 shows how the sedimentation time necessary to create a dust coating of a given density (20 mg cm^{-2} in the example of Table 2) decreases with increasing wind speed. The rippled surface of the coating created at $u_f = 0.63$ m s^{-1} is almost fully mature and contains no open spaces between the ripples, whereas the coating created at $u_f = 2.59$ m s^{-1} is only 9.3 min old and is still in its primary stage of development. The heterogeneous structure of the latter coating was clearly observable during the experiments, and there is no doubt that it is the major cause of the higher PV cell performance compared to the lower wind velocities.

Table 2. Height and spacing of the dust ripples on the PV cell (data refer to a dust density of 20 mg cm^{-2})

Wind velocity (m s^{-1})	Sedimentation time (min)	Ripple height (cm)	Ripple spacing (cm)
0.63	53.2	0.0103	0.07
1.37	16.9	0.0059	0.23
1.86	11.1	0.0046	0.25
2.59	9.3	0.0037	0.30

Comparing the wind velocity's aerodynamic and sedimentological effects, we note that the former is far more dominant. Small differences in wind velocity may lead to significant differences in PV cell performance, whereas the effect of the wind on the sedimentological structure of dust coatings always remains small (at least in terms of PV cell performance), even when differences in wind speed are high.

5.3. Recommendations for the installation of PV modules in deserts and other polluted areas

Since high wind velocities and high air dust concentrations result in high dust deposition, PV modules in deserts and other polluted areas should preferably be installed at locations where: (1) wind velocity is low; (2) airborne dust concentration is low. In sufficiently hilly areas, the easiest (and also cheapest) solution is to make use of the benefits provided by the natural topography (e.g. hills, slopes and valleys) near the solar plant site. In several previous studies, Goossens (1996), Goossens and Offer (1990, 1993) and Offer and Goossens (1995) investigated the effect of topography on aeolian dust deposition and accumulation. These studies showed that lowest deposition (and accumulation) occurs either on the leeward side of hills or immediately downwind of sharp topographic transitions (such as terraces, or steep slopes abruptly passing into near-horizontal surfaces, for example a plateau surrounded by steep slopes). At such locations, both wind velocity and airborne dust concentration are low, and so will be the deposition and accumulation. Field measurements in the Negev desert have shown that dust accumulation in the lee of hills may be up to four times less than on windward slopes, and up to 50% less than on flat, horizontal surfaces (Goossens and Offer, 1990, Goossens and Offer, 1993; Offer and Goossens, 1995). Care should be taken, however, that the benefit of a smaller dust accumulation is not compensated by the shadow caused by the hills.

Within a solar plant, the position of PV collectors and the orientation of collector arrays should be such that downwind collectors optimally benefit from the effects upwind collectors exert on the dust particle trajectories. Collector spacing should be such that the modules of a collector are still within the dust shadow created by the upwind adjacent collector, without suffering from the latter's light shadow. In addition, collectors should be arrayed such that wind (and dust) funnelling within the plant is avoided.

Finally, new collectors should be designed in such a way that they provide optimum protection against dust deposition on the module surfaces.

A careful study, including both wind tunnel simulations and field measurements at the site, should precede any construction of a new solar plant in heavily polluted areas.

6. CONCLUSIONS

The deposition (and accumulation) of fine aeolian dust particles on the glazing of PV cells significantly affects the performance of such cells. The role of two meteorological parameters, wind velocity and airborne dust concentration, on the performance drop was investigated. This was done via controlled experiments in an aeolian dust wind tunnel.

Wind velocity has an important impact on cell performance drop. High wind speeds lead to high dust accumulation on a cell, resulting in sharp performance drops. In cases of low wind, dust accumulation is smaller, and the drop in cell performance is less expressed. But the wind also has an impact on the sedimentological structure of the dust coating on the cell: light transmittance is higher in coatings created in high winds than in coatings created in low winds, resulting in larger performance drops during low winds. The experiments indicate that the former effect is much more important than the latter, so in general the drop in PV cell performance due to dust accumulation is greater in high winds.

Airborne dust concentration also affects the drop in PV cell performance since high dust concentrations lead to high accumulation values on the cell surface. But, contrary to wind speed, airborne dust concentration does not seem to affect the transmittance of light in the coatings on solar cells.

The reader should be aware that the following restrictions apply to this study:

1. The range of wind speeds tested was between 0.63 $\mathrm{m\,s^{-1}}$ and 2.59 $\mathrm{m\,s^{-1}}$. For instrumental reasons, no larger wind speeds were possible during the experiments (although the wind tunnel itself is capable of generating higher winds). However, these values closely approach the average background speed in most deserts, so the numerical results of the wind tunnel experiments should be interpreted in terms of long-term dust accumulation (not the accumulation during one single, heavy storm).
2. To keep the duration of the wind tunnel experiments within reasonable limits the airborne dust concentrations used in the tunnel were rather high (though not unrealistic), but it is unlikely that this simplification affects the general trends observed. Many simulations with similar high concentrations executed earlier in the Leuven wind tunnel were later tested in field experiments, and the wind tunnel results were always very close to the field data.
3. The PV cell was always put horizontally into the wind tunnel (i.e. parallel to the wind flow). This is an important simplification, since fixed mounted PV modules are usually positioned with an inclination angle of at least 10°. As pointed out in Section 5.3, the inclination angle is an important factor with respect to dust deposition. However, including the inclination angle as a separate parameter in this study would have increased the number of wind tunnel simulations considerably. Because of its importance, the effect of inclination angle deserves a more profound study focusing on this aspect alone, and, therefore, we decided to keep it, for the time being, outside the scope of this paper. Previous dust experiments by Smits and Goossens (1995) on tilted surfaces of a thermic collector showed that dust accumulation was largest on horizontal surfaces, and that was one of the reasons why it was decided to put the solar cell in a horizontal position in the wind tunnel.
4. All experiments were executed in a wind tunnel, i.e. an environment where the airflow is quite constant and the turbulence level is low. In the natural environment, more temporal (and spatial) variability occurs, but it is unlikely that this affects the general conclusions of this study. As pointed out earlier, many simulations conducted earlier in the Leuven wind tunnel were later tested in field experiments, and the wind tunnel results were always confirmed in the field.
5. The numerical results presented in this paper only refer to the dust type used (Belgian Brabantian loess). For other dust types and sizes, the numerical results will be different, but it is very unlikely that the general trends described in this paper would be different for other dusts.
6. All experiments were executed with one single type of PV cell. Again, it is reasonable to assume that the trends observed apply to most other PV cells.

Despite these restrictions, the experiments conducted provide us with a general idea of the effects of wind velocity and airborne dust concentration on the drop of photovoltaic solar cell performance due to dust pollution on the cells.

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