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Influence of dust deposition on photovoltaic panel performance

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Abstract

Solar photovoltaic power plants are ideally located in regions with high insolation levels. Photovoltaic performance is affected by high cell temperatures, soiling, mismatch and other balance-of-systems related losses. It is crucial to understand the significance of each of these losses on system performance. Soiling, highly dependent on installation conditions, is a complex performance issue to accurately quantify. The settlement of dust on panel surfaces may or may not be uniform depending on local terrain and environmental factors such as ambient temperature, wind and rainfall. It is essential to investigate the influence of dust settlement on the operating characteristics of photovoltaic systems to better understand losses in performance attributable to soiling.

The current–voltage (I–V) characteristics of photovoltaic panels reveal extensive information to support degradation analysis of the panels. This paper attempts to understand performance losses due to dust through a dynamic study into the I–V characteristics of panels under varying soiling conditions in an outdoor experimental test-bed. Further, the results of an indoor study simulating the performance of photovoltaic panels under different dust deposition regimes are discussed in this paper.

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Keywords: Photovoltaic performance; Dust deposition; Experimental test-bed; Indoor simulation; Power losses.

1. Introduction

Over the last two decades, there has been a steady rise in the installed capacity of solar photovoltaic (PV) power plants across the globe. While the increase in the contribution of photovoltaic power to the energy production pie and steady improvements in photovoltaic material efficiencies are certainly encouraging, it is essential that these PV installations operate at their maximum design capacities to ensure a consistent and reliable power delivery over the

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lifetime of the plant. Environmental parameters such as ambient temperatures, and local wind and dust regimes can significantly affect system performance. The effects of ambient and cell temperatures on PV system performance are fairly well understood theoretically and validated through wind tunnel simulations. However, losses in performance attributable to dust deposition is an issue that has not been dealt with comprehensively in previous studies, since it is complex to accurately quantify. Studies by Nahar and Gupta [1] and Said [2] show that performance may decrease by up to 20% every month by the accumulation of dust on unclean cell surfaces. Moreover, experiments conducted by Goossens and Van Kerschaever [3] indicate that high wind speeds promote dust accumulation on surfaces. No studies yet have been conducted to correlate the quantity of dust deposition and resultant drops in PV performance.

Tropical regions such as the Indian subcontinent, the Middle-East, Saharan Africa and the south-western United States are particularly vulnerable to the accumulation of dust on PV installations. Mani and Pillai [4] report that dust-related degradation in PV performance is worse in tropical regions where arrays are installed with lower tilt angles. The settlement of dust and sand on cell surfaces may be uniform or non-uniform depending on the size of the PV arrays and the terrain of the location. Smaller panels may have uniform dust accumulation and the drops in panel performance may be identical for several panels in the array. However, the pattern of dust accumulation may not be uniform for panels with larger areas or panels that are positioned at large distances from each other in the module. Therefore the drops in panel performance due to dust deposition may not be identical over the entire array and hence more difficult to predict for such an installation. Ambient wind and rainfall are thought to be natural cleaners of dust from PV surfaces. On the contrary, it is seen that wind and rainfall often encourage the settlement of dust on PV surfaces. Rao et al. [5] verified on an experimental test-bed that high wind speeds increase the tendency of dust deposition on PV surfaces and cause drops in panel power output. Rainfall aids in cleaning PV surfaces when the water aids the removal of dust particles as it drains off the surface. However, if rainwater evaporates from the PV surface without draining off, it causes stronger adhesion of dust on the surface. It is of essence to investigate the influence of dust settlement on PV system performance to comprehend the losses in performance attributable to soiling alone. This would help an appreciation of the enormity of the problem of dust deposition in terms of potential energy delivery losses to the grid and of estimating economic losses to the power plant. Such an investigation would also facilitate feasibility studies of cleaning mechanisms and the development of appropriate cleaning schedules.

The direct impact of dust deposition on PV system performance can be gauged by a comparison of the current-voltage (I-V) characteristics of the panels with and without dust settlement on their surfaces. The I-V characteristics can be considered the ‘fingerprint’ of the photovoltaic element under study as every PV element produces a unique I-V curve whose shape depends on the conditions of insolation, ambient temperature, cell operating temperature, wind incidence, soiling and mismatch losses and other balance-of-system related losses at the instant it is traced. Hence, comparing the I-V characteristics of two identical panels keeping all ambient factors same but varying one, enables the isolation of the influence of that particular factor on system performance. This comparative approach has been adopted in the present study to investigate the influence of dust deposition on PV operating characteristics, while keeping the panels exposed to identical ambient parameters but with differing quantities of dust deposition.

2. Methods and instrumentation

A two-fold method was employed to obtain I-V curves from two identical panels, one panel with dust deposition and the other panel devoid of dust. In the first method, I-V readings were recorded from panels placed in an indoor environment and illuminated by solar simulating halogen lamps. The second method comprised of recording I-V characteristics from identical panels installed on an outdoor experimental test-bed and exposed to natural sunlight. Both panels in either setup were subjected to identical ambient conditions and differed only in their dust depositions. These two setups are detailed in the following subsections.

Nomenclature

I_{sc}	short circuit current
V_{oc}	open circuit voltage

2.1 Indoor solar simulator setup

The specifications for the polycrystalline PV panels used for this study are listed in Table 1 below.

Dimensions	
Module dimensions (mm x mm)	675 x 485
Cell dimensions (mm x mm)	155 x 40
Cells per module (units)	36
Cell area per module (m ²)	0.2232
Electrical specifications	
Maximum power (W)	37.0
Voltage at maximum power (V)	17.0
Open circuit voltage (V)	21.0
Current at maximum power (A)	2.17
Short circuit current (A)	2.40

For the indoor solar simulation, two identical panels of the specified ratings were installed side-by-side parallel to the ground. The panels were placed in a dark room and the only illumination on the panels was from a pair of sun-simulating halogen lamps whose intensity could be varied, suspended vertically above each panel, shown in Fig. 1. One of the panels was maintained free of dust through the duration of the solar simulations, whereas the other panel had dust deposited on its surface. In Fig. 1, the panel on left was cleaned of dust while the panel on right was not. The I-V characteristics were plotted and logged using MECO solar module analyzers. The intensity of the lamps was measured and set using a TENMARS solar power meter and a CENTER infrared thermometer was used to measure the lower surface temperature that is considered a good approximate of the cell operating temperature [6].



Fig. 1. Indoor solar simulator setup.

The I-V characteristics for the indoor solar simulator setup were recorded in two batches of readings. With a view to eliminate the effect of rise in cell operating temperature on the performance of the panels during operation, the first set of data was logged varying the intensity of light incident on the panels from 200 W/m^2 to 800 W/m^2 while maintaining the temperatures of the panels constant. The I-V curves so obtained in this first set are therefore independent of the influence of cell temperature on the performance of the two panels. In the second set of recordings, the intensity of the incident light was again varied from 200 W/m^2 to 800 W/m^2 in steps of 100 W/m^2 while allowing the cell surfaces to attain their maximum temperatures at those insolation levels. The results of the test conducted on the indoor solar simulator setup have been reported and discussed in the forthcoming section.

2.2 Outdoor experimental test-bed

The experimental readings for the second phase of this investigation were recorded on an outdoor test-bed installed on the rooftop of the Centre for Sustainable Technologies at the Indian Institute of Science, Bangalore (latitude 12.97°N , longitude 77.56°E). The test-bed consisted of two identical open-rack mounted polycrystalline silicon photovoltaic panels installed side-by-side and tilted at 13° to the ground facing southwards. Both panels experienced the same instantaneous insolation levels, ambient temperatures and wind incidence. The arrangement for the outdoor experimentation is depicted in Fig. 2.

The PV panels used for the outdoor experimentation were exactly identical to the ones used for the indoor setup, the specifications for which have been enlisted in Table 1. Like in the earlier situation, the I-V characteristics for the panels were plotted and logged using MECO solar module analyzers and the plane-of-array insolation was measured using the TENMARS solar power meter. The cell surface temperatures were measured using K-type thermocouples and were recorded through BrainChild transducing IO modules. The thermocouple sensors were kept in contact with the panel surfaces using a silver-epoxy based heat conducting paste. The I-V characteristics in this case too were recorded in two batches. The first set of readings were taken when both panels had equivalent amounts of dust deposited on their surfaces, in order to characterise the performance of the two panels under identical ambient conditions and dust depositions. For the second batch of measurements, the panel on left in Fig. 2 was cleaned and the dust so collected was weighed to approximate the amount of dust that remained deposited on the dusty panel, seen on the right hand side in Fig. 2. The outdoor experimental results have been described in the following section.



Fig. 2. Outdoor experimental test-bed.

3. Results and discussions

The indoor setup facilitated greater control of the test conditions than the outdoor test-bed. Since the indoor tests were carried out in a dark, enclosed space, the incident light on the panels could be adjusted to desired values and maintained constant for long periods of time. Furthermore, by switching off the lamps, the panels could be brought back to the ambient temperature in the room, which remained more or less constant for the duration of the studies. This allowed a more comprehensive examination of the phenomenon of dust affecting the panel I-V characteristics. The indoor solar simulation was repeated on the outdoor experimental test-bed in order to verify if similar behaviour could be observed under natural conditions of solar radiation and ambient temperatures. In both situations, the I-V characteristics of the panel that had accumulated dust were compared against those of the clean panel.

3.1 Indoor solar simulator setup

Of the two panels used for the indoor simulation setup, one panel was completely cleaned of dust, while the second panel had a visible quantity of dust deposited on the surface. The microscopic images in Fig. 3 reveal the dust deposition on the panels. It may be noted that nearly 70% of the surface area of the second panel was covered by dust particles. In the first set of readings, the I-V curves were plotted at an intensity of 400 W/m^2 at two different cell surface temperatures viz. 40°C and 50°C (Fig. 4), and in the second case, when the temperatures of both panels were close to the ambient temperature in the room. The intensity of the halogen lamps was increased in steps of 100 W/m^2 starting from 200 W/m^2 going up to 800 W/m^2 which was the maximum light intensity of the lamps. All the readings were recorded when the panel temperatures had reached 30°C . The I-V curves obtained from the two panels at 200 W/m^2 , 400 W/m^2 , 600 W/m^2 and 800 W/m^2 have been reproduced here in Figs. 5-8 respectively.

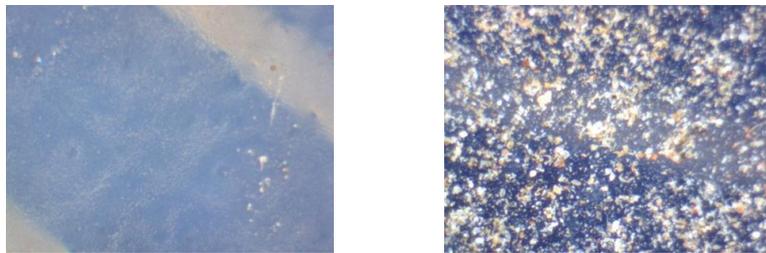


Fig. 3. Microscopic images (150x) of cell surfaces on the clean panel (L) and the dusty panel (R).

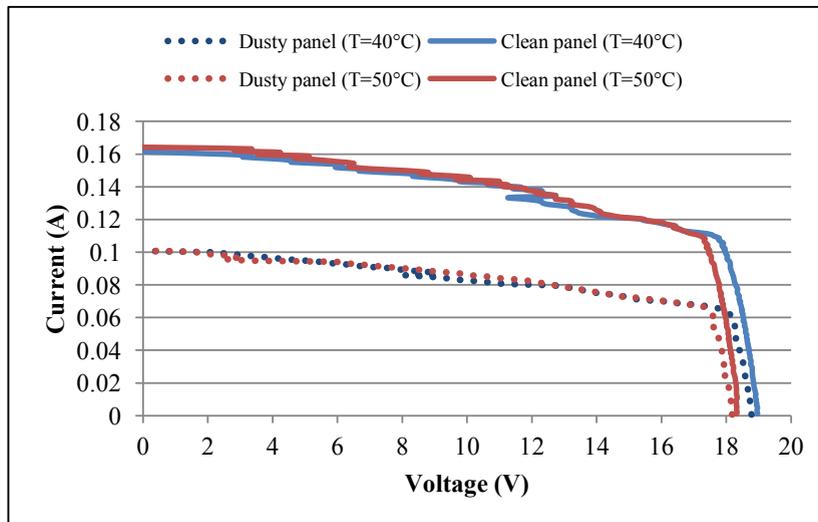


Fig. 4. I-V characteristics at 400 W/m^2 and cell surface temperatures of 40°C and 50°C .

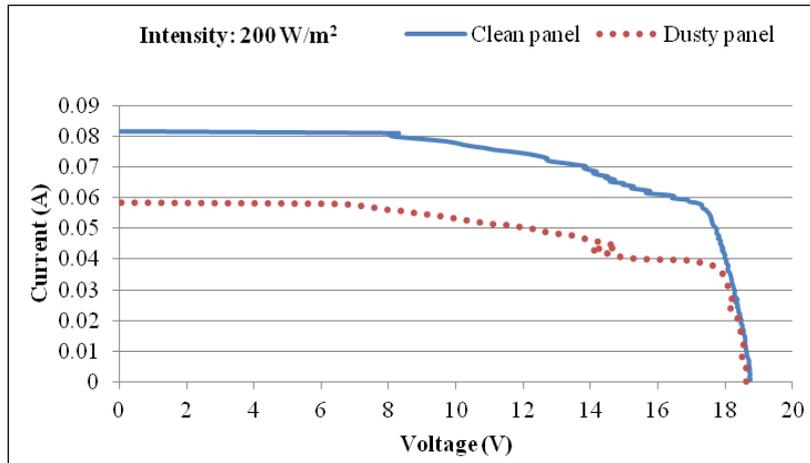


Fig. 5. I-V characteristics at 200 W/m² and cell surface temperatures of 30°C.

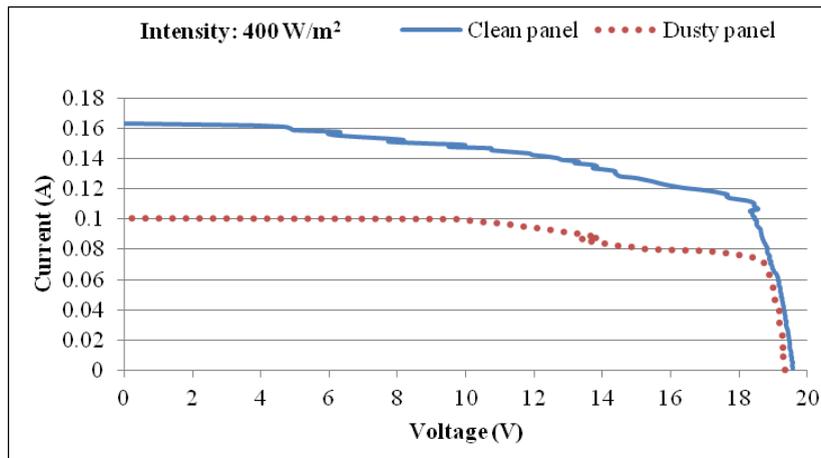


Fig. 6. I-V characteristics at 400 W/m² and cell surface temperatures of 30°C.

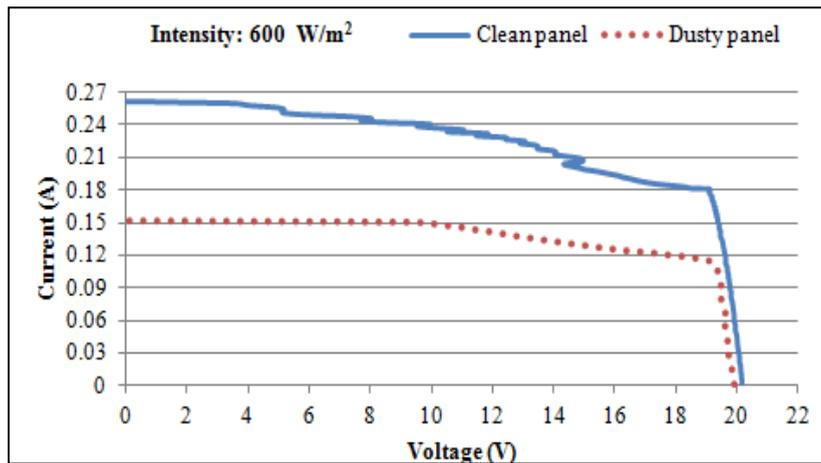


Fig. 7. I-V characteristics at 600 W/m² and cell surface temperatures of 30°C.

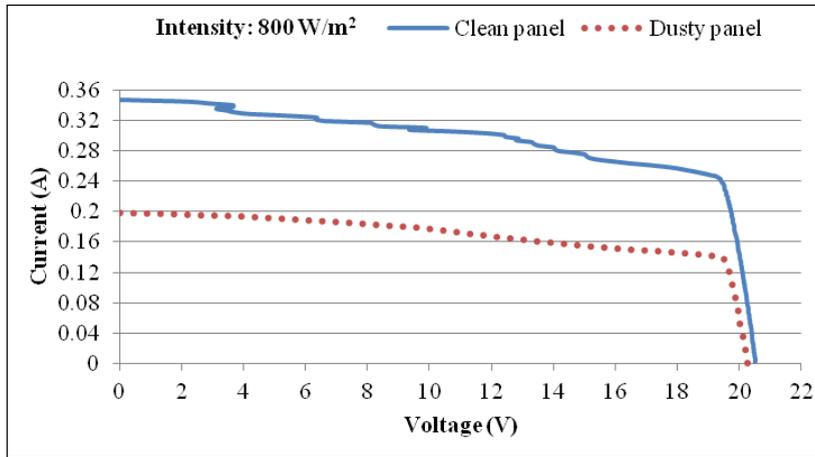


Fig. 8. I-V characteristics at 800 W/m² and cell surface temperatures of 30°C.

Table 2. Recordings of the indoor simulation study.

Intensity (W/m²)	Cell temperature (°C)		Average power output (W)		Short circuit current (A)		Open circuit voltage (V)		I _{sc} (dusty) / I _{sc} (clean)	V _{oc} (dusty) / V _{oc} (clean)
	Clean	Dusty	Clean	Dusty	Clean	Dusty	Clean	Dusty		
200	40.68	42.32	0.84	0.58	0.073	0.048	17.72	17.64	67.05	99.57
300	41.30	42.57	0.98	0.64	0.082	0.054	17.86	17.69	66.12	99.05
400	49.84	50.90	1.84	1.11	0.157	0.097	18.26	18.07	62.09	98.91
500	51.22	52.27	2.83	1.69	0.233	0.136	18.59	18.33	58.49	98.58
600	52.60	54.88	3.31	1.96	0.269	0.158	18.63	18.38	59.13	98.67
700	54.99	56.37	3.86	2.33	0.312	0.181	18.62	18.39	58.09	98.81
800	62.42	64.65	3.97	2.47	0.339	0.195	18.36	18.13	57.37	98.75

Table 2 above enlists the recordings at different intensities of the average power outputs, short circuit currents, open circuit voltages and the cell temperatures noted at that intensity.

From the recordings and the graphs, the following observations can be drawn:-

1. It may be noted from the graphs that dust deposition does not have a sizable effect on the open circuit voltage of the panels. The open circuit voltage of the dusty panel is only slightly lower than that of the clean panel at all light incidence intensities. This is confirmed by the last column in Table 2 which lists the ratio of the open circuit voltage of the dusty panel to the open circuit voltage of the clean panel. This ratio remains close to 100% for all light incidence intensities. It is postulated hence that dust does not largely affect system voltage.
2. However, dust has a significant effect on the short-circuit current produced by the panels. The clean panel consistently produced a higher current output than the dusty panel. This difference in the current outputs widened as the incident light intensity increased from 200 W/m² to 800 W/m², i.e. the current output of the dusty panel decreased with an increase in the incident light intensity as can be seen in the penultimate column of Table 2 which lists the ratio of short circuit current of the dusty panel to the short circuit current of the clean panel. Dust deposition therefore has a significant effect on the current output of photovoltaic systems.
3. The dust collected from the cleaned panel in the indoor setup was weighed to be 1.846 grams spread over a surface area of 0.258 m², i.e. a dust density of 7.155 g/m². The power losses associated with this dust density is 45-55% of the maximum possible power output with a dust-free photovoltaic system.

4. Dust deposition on panels has an influence on the cell operating temperatures. The dusty panel was noted to be operating 1-2°C higher than the clean panel for the same light incidence. This increase in cell temperature due to dust further reduces the electrical efficiency of the panel.
5. A rise in cell surface temperatures from 40°C to 50°C led to a slight increase in the short circuit current of both the clean and dusty panels which was however accompanied by a larger drop in open circuit voltage causing an overall loss in power output due to rise in operating temperature. The combined effect of dust deposition and rise in cell surface temperatures is therefore to further deteriorate the system performance.

3.2 Outdoor experimental test-bed

The panels installed on the outdoor experimental test-bed were checked to compare their performance under identical dust deposition regimes and their I-V characteristics were found to be nearly identical as seen in Fig. 9. We can safely assume that the dust deposition on both the panels was identical. After this check, one of the panels was cleaned of dust while the dust on the second panel remained undisturbed. The I-V characteristics of the two panels were recorded at five minute intervals on a typical Bangalore day in September. The I-V curves obtained from the panels for three insolation levels, viz. 333 W/m², 525 W/m² and 925 W/m² have been plotted in Figs. 10-12 below.

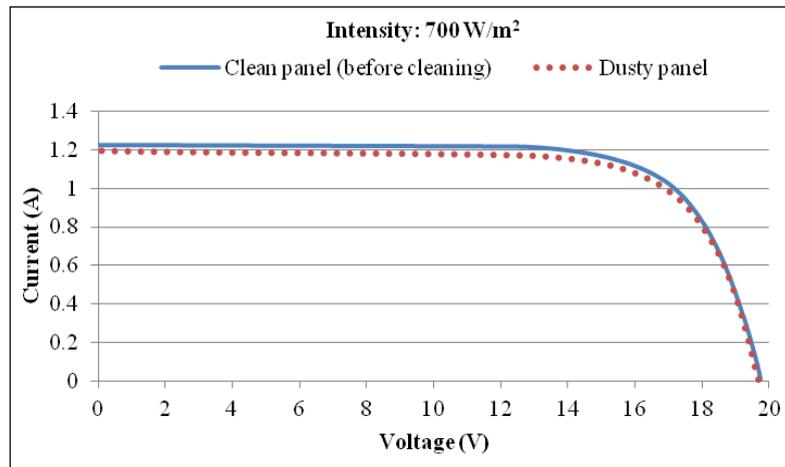


Fig. 9. I-V characteristics of both panels with identical dust deposition on their surfaces.

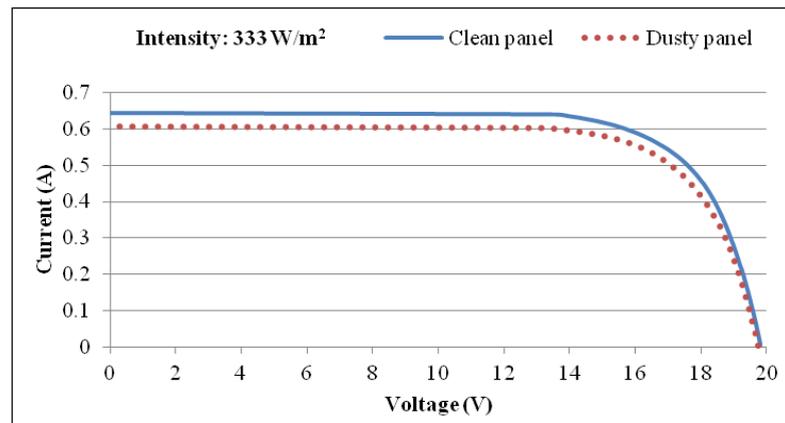


Fig. 10. I-V characteristics at an insolation of 333 W/m².

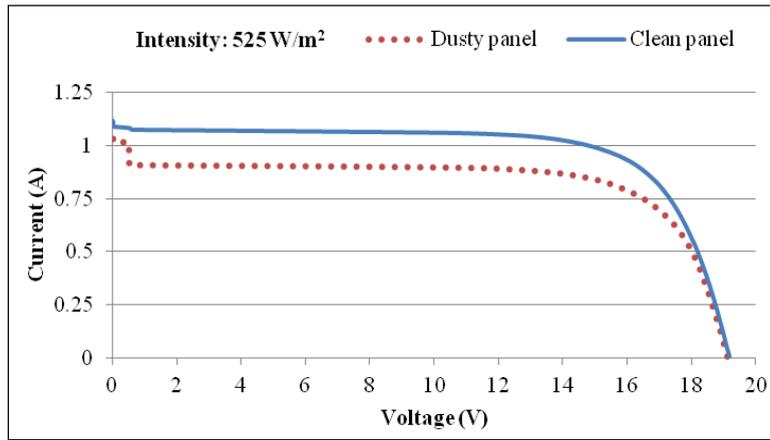


Fig. 11. I-V characteristics at an insolation of 525 W/m².

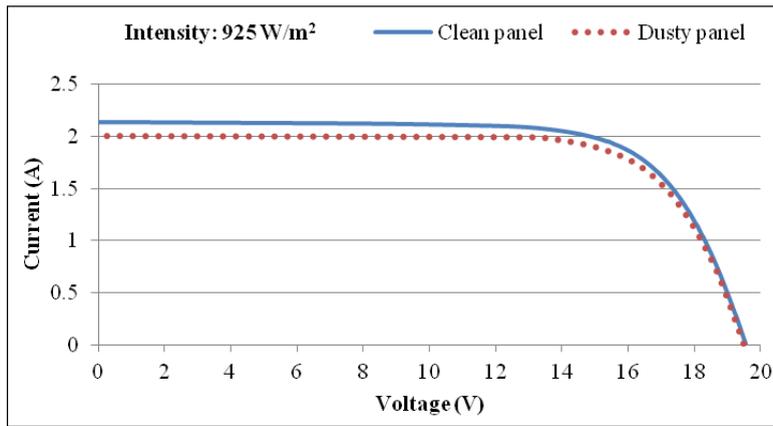


Fig. 12. I-V characteristics at an insolation of 925 W/m².

Table 3 enlists the recordings at different intensities of the average power outputs, short circuit currents, open circuit voltages and the cell temperatures noted at that intensity.

Table 3. Recordings of the outdoor experimental study.

Intensity (W/m ²)	Cell temperature (°C)		Average power output (W)		Short circuit current (A)		Open circuit voltage (V)		I _{sc} (dusty) / I _{sc} (clean)	V _{oc} (dusty) / V _{oc} (clean)
	Clean	Dusty	Clean	Dusty	Clean	Dusty	Clean	Dusty		
264	34.0	34.0	7.00	6.49	0.516	0.484	19.51	19.40	93.80	99.44
290	33.1	33.1	8.34	7.81	0.579	0.547	19.78	19.69	94.47	99.54
333	34.0	34.0	9.43	8.86	0.643	0.606	19.81	19.73	94.25	99.60
335	35.6	35.7	9.48	8.83	0.661	0.618	19.69	19.61	93.49	99.59
525	45.8	46.4	14.94	12.69	1.116	1.048	19.22	19.14	93.91	99.58
870	51.6	52.4	21.54	20.90	1.486	1.397	19.18	19.14	94.01	99.79
900	43.8	43.9	23.91	28.39	1.694	1.574	20.40	20.29	92.92	99.46
920	57.1	57.0	30.02	28.67	2.135	1.999	19.59	19.52	93.63	99.64
925	54.5	54.0	33.80	32.93	2.188	2.053	19.85	19.79	93.83	99.70

From the recordings and the graphs, the following observations can be drawn:-

1. It is again noted from the graphs that dust deposition does not have a sizable effect on the open circuit voltage of the panels. The open circuit voltage of the dusty panel is only slightly lower than that of the clean panel at all light incidence intensities. This is confirmed by the last column in Table 3 which lists the ratio of the open circuit voltage of the dusty panel to the open circuit voltage of the clean panel. This ratio remains close to 100% for all light incidence intensities. It is proposed therefore that dust does not largely affect system voltage.
2. Under natural sunlight, dust has a slight adverse effect on the short-circuit current produced by the panels. The clean panel consistently produced a higher current output than the dusty panel. But this difference in the current outputs was not as dramatic as observed in the indoor simulation. The ratio in the penultimate column of Table 3 ranges between 92-94%. Moreover, there was no clear relation of the drop in current output due to dust deposition, with insolation level as observed in the indoor setup. This difference in current reduction may be due to the disparity in the spectrum of light emitted by the halogen lamps and the solar spectrum.
3. The dust collected from the cleaned panel in the indoor setup was weighed to be 0.363 grams spread over a surface area of 0.258 m², i.e. a dust density of 1.4 g/m². A 0.5-1.5W drop in power output was observed due to dust deposition. The power losses associated with this dust density is 5-6% of the maximum possible power output with a dust-free photovoltaic system. The effect of dust in reducing power output will become more prominent when scaled up from a small experimental test-bed to a large-sized photovoltaic power plant.
4. A correlation is noticed between dust deposition density and the power losses associated with dust settlement on photovoltaic panels. In the case of the outdoor experimental setup where the dust density was found to be 1.4 g/m², the power loss due to dust was 5-6% of the maximum power output, whereas in the case of the indoor simulation setup where the dust density was 7.155 g/m², the associated power loss was 45-55% of the maximum possible power output from a clean panel. This correlation merits further investigation.
5. No significant differences in cell operating temperatures were observed due to dust deposition on the test-bed.

4. Conclusions

The present study was conducted to gain preliminary insight into the influence of dust deposition on photovoltaic system performance. The study involved simulations on panels in an indoor setup as well as experimentation on panels in an outdoor test-bed. The effect of dust on panel performance was investigated by obtaining I-V characteristics of identical panels subjected to the same conditions of insolation and ambient temperature, while one of the panels retained dust on its surface whereas the other was cleaned of dust. A comparative analysis of the I-V curves led to an understanding of the phenomenon of power loss due to dust accumulation on photovoltaic surfaces.

It was observed that dust deposition does not significantly alter the open circuit voltage of photovoltaic systems. However, the short circuit current is affected by dust deposition, to the tune of 30-40% in the indoor setup and 4-5% in the outdoor test-bed. This drop in current output and the consequent drop in power output due to dust is an immense loss of electrical power and economic loss to photovoltaic power plants considering the scale of the plants.

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