

Performance of photovoltaic generators under superficial dust deposition on their modules derived from anthropogenic activities

Alessandra Comerio¹, Thiago Tassinari Scarpat², Rafael Cabral Knaip Krause², Mariana Rampinelli Fernandes², and Pablo Rodrigues Muniz^{2*}

¹Programa de Pós-Graduação em Engenharia Elétrica, Universidade Federal do Espírito Santo, Vitória, Espírito Santo, Brazil. ²Instituto Federal do Espírito Santo, Av. Vitória, 1729, 29040-780, Vitória, Espírito Santo, Brazil. *Author for correspondence. E-mail: pablorm@ifes.edu.br

ABSTRACT. Performance of photovoltaic generators is affected by, among other factors, surface dust deposition on photovoltaic modules, which causes uniform soft shading, reducing the solar radiation reaching photovoltaic cells. Several researches have demonstrated this effect through studies in specific localities. As deposition of particulate matter varies according to locality, these results cannot be generalized or used in other places, since these studies do not characterize their local dust. Considering these research opportunities, this paper evaluates the deposition effects on photovoltaic modules by different types of dust from anthropogenic activities recurrent in urban areas, a typical situation of distributed microgeneration. Particulate matter of iron ore, building construction, quarry, and mineral coal are characterized morphologically and dimensionally. Then, their effects on photovoltaic module performance are analyzed under different deposition densities according to typical urban deposition rates. The results show that the different dust materials studied attenuate the power generation capacity to different extents, and superficial dust density of the particulate matter also produces different effects. These results can be used in performance and economic feasibility analyzes of photovoltaic generators in different locations with similar pollution characteristics.

Keywords: solar power generation; photovoltaic systems; dust effect; particulate matter; performance evaluation; urban pollution.

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Introduction

Electric power is paramount today. With the growth of global economy and rising concerns for the environment since the 1990s, clean energy has become a world-wide focus (Wang, Wang, & Su, 2011; Shaddel, Javan, & Baghernia, 2016), thus increasing the renewable energy contribution to the world's energy matrix.

Capex and Opex costs are an important aspect to be considered in deployment of renewable energy sources. There has been a significant reduction in the cost of the main elements of electric power generation systems from renewable sources, which has made this type of energy attractive. According to (Shaddel et al., 2016), among the different types of renewable energy sources, solar energy is one of the best alternatives for fossil fuels because of its abundance and environmentally friendly characteristics. Solar energy lends itself to the installation of small and medium scale plants in residential and commercial buildings (Pereira et al., 2017) in urban areas, not requiring exclusive and dedicated areas typically away from large populated centers for their installation.

Photovoltaic (PV) modules in operation are subjected to the deposition of sediment material from atmospheric pollution. These suspended particles can be derived from anthropogenic and natural processes or produced in the atmosphere (Kaldellis & Kapsali, 2011). Dust particles accumulate on the surface of PV modules, an indirect effect of air pollution, causes the so-called soft shading (Sarver et al., 2013). It is known that uniform distribution of dust on the PV module surface can attenuate the solar radiation incident

on the PV cells, which negatively affects its performance (Michels et al., 2015; Bergin, Ghoroi, Dixit, Schauer, & Shindell, 2017). Researchers at Duke University have found that this dust deposition can reduce the energy performance of PV installations by up to 25% in countries such as China, India, and the Arabian Peninsula (Bergin et al., 2017). Also, it is noteworthy that the reduction in energy generation varies according to the composition, size, and type of the particle (El-Shobokshy & Hussein, 1993). Therefore, it is important to establish the effects of different levels and types of dust on energy production and to estimate an acceptable maximum limit of particles that would not impact the energy production.

An extensive review performed by the authors on studies concerning effects of dust deposition on PV modules, shows that researchers evaluated the reduction in energy generation by PV modules as a function of their inclination angles, time of exposure to atmosphere, and location of installation. Only a few of these studies characterized PM by stating the particle diameter, or by a generic definition, like 'ash', 'soil', and 'sand', etc., or based on the PV generator location, like 'desert', 'next to volcano', etc., making unfeasible their application in other locations (Abderrezek & Fathi, 2017; Ali et al., 2017; Bergin, et al., 2017; Fountoukis, Figgis, Ackermann, & Ayoub, 2018; Fraga, Campos, Almeida, Fonseca, & Lins, 2018; Gholami, Khazaei, Eslami, Zandi, & Akram, 2018; Guan, Zhang, Xiao, Zhou, & Yan, 2017; Klugmann-Radziemska, 2015; Paudyal & Shakya, 2016; Ramli et al., 2016; Saidan, Albaali, Alasis, & Kaldellis, 2016; Styszko et al., 2019; Tanesab, Parlevliet, Whale, & Urmee, 2015, 2016, 2017; Tripathi, Aruna, & Murthy, 2017).

Notwithstanding the large PV plants, the quantity and total power of PV units in distributed generation (DG) have grown in several countries (Menezes, Muniz, & Fiorotti, 2018; Hess, 2016; Zhang, 2016). Thus, the generation of PV energy is subject to different types and concentrations of dust, considering large power plants in eroded areas and PV units in DG submitted to the different particulate matter (PM) present in urban areas.

Since many studies have already been performed in uninhabited areas, and generation of PV energy in DG in urban areas has grown, the objectives of this study were to evaluate the impact of different kinds of dust deposition from anthropogenic activities common in urban environments (typical locations of PV units in DG) on the performance of PV modules, considering different deposition rates of the PM, and to produce the results that can be applied to different urban locations.

Material and methods

This study analyzed the scientific hypothesis that electric power generation capacity of the PV module is attenuated in different ways, depending on the dust deposited on its surface, and that increased surface density of dust causes a decrease in the generation of electric energy.

Variables of the studied system

In order to choose the types of PM to be studied, studies carried out in several parts of the world were considered, namely the United States of America, Greece, France, Mexico, China, and Brazil (Liu et al., 2015; Pandis et al., 2016; Santos et al., 2017). The most recurrent sources of PM studied are:

- material originating from automobile traffic (transport sector), typically resuspension;
- industrial emissions;
- urban dust;
- soil;
- coal combustion;
- biomass burning.

Particulate matter may be suspended in the atmosphere for long periods and deposited at different distances from the source depending on its diameter; the larger the particle diameter, the closer to the source does sedimentation occur (Santos & Reis Jr., 2011). Studies on the chemical and morphological characteristics of sedimentary dust in Brazil have concluded that approximately 90% of the sedimentary material in a given urban area originated from industrial activities and found that their diameter ranged from (5 to 100) μm (Santos & Reis Jr., 2011; Santos et al., 2017).

Therefore, in this research the following PM were used to represent urban pollution:

- iron ore powder, which represents emission from the steel industry;
- quarry powder (grit), which represents emission from the stone mineral extractive industry;
- building dust, which is intrinsic to urban areas; and
- mineral coal powder, which represents emission from the logistics industry and beneficiation of this natural resource.

Another independent variable determined was the dust surface density. The range of analysis of which was measured as a function of typical deposition rates in urban regions, namely, (2.5, 5.0, and 10.0) g m⁻². These dust deposition values were adopted as representative of reported rates of deposition in urban environments, typically ranging from (6 to 14) g m⁻² month⁻¹ (Santos & Reis Jr., 2011). Therefore, the range of analysis amounts periods of 4 to 50 days of exposure to deposition without cleaning service.

The dependent variable, i.e., output, was the electric power generation capacity of the PV modules.

All measurements were performed on three experimental modules (loaded with dust) simultaneously with a reference module (clean), so that both the reference module and the modules under analysis were subjected to the same influences, thereby minimizing the influence of measurement errors and the propagation of uncertainties (Gonçalves Júnior & Sousa, 2018).

Other variables such as module temperature, solar irradiance, shading, wind speed, relative air humidity, (experiment site) temperature, type of materials used in the PV module construction, and natural degradation of PV cells also affect the electric power generation capacity (Mekhilef, Saidur, & Kamalisarvestani, 2012; Kaldellis, Kapsali, & Kavadias, 2014; Said & Walwil, 2014; Fouad, Shihata, & Morgan, 2017; Said, Hassan, Walwil, & Al-Aqeeli, 2018). In this experiment, these other variables were classified as spurious variables, since they were not of interest for the research. To annul the interference of these variables, the PV modules were installed at the same inclination, exposed to the same environmental conditions, and were unused modules. Natural degradation of the modules can be disregarded, as the experiment duration was only a certain number of days, which is relatively irrelevant when compared to the decades of life-span expected of the modules.

In order to cancel out the variability due to any possible construction differences between the modules, another spurious variable, the modules initially were comparatively characterized in a non-deposition condition. In this way the electrical energy production of each of the three experimental modules were determined in relation to the reference module.

Another factor that may influence the results is surface deposition of additional atmospheric dust on the modules during the experiment. However, considering the short experiment timespan of approximately 6 hours, it is concluded that this deposition of dust is irrelevant, about 1% of the experimental deposition, about some days of deposition.

Measurements were performed at 5 min intervals. For each experiment 72 measurements were taken. Each experiment consisted of a combination of two input variables, one with four qualitatively different types of dust and the other with three quantitatively different levels of dust deposition, making up 12 combinations. Thus, a total of 864 measurements were taken.

Experimental PV system

The PV system set consisted of 4 independent polycrystalline PV modules model TP660P from the manufacturer Talesun Solar Technologies, with output power of 270 Wp each. Each PV module had 1.63 m² useful area.

The APSystems microinverter system consisted of two main elements: microinverter and ECU (Energy Communication Unit).

Each PV module is connected individually to an APSystems microinverter model YC500A. This setup provides each module a unique Maximum Power Point Tracker (MPPT), which ensures that maximum power of each module is achieved regardless of the performance of the other PV modules in the system, eliminating the need of analyzing and comparing their characteristic curves.

For the acquisition of electricity generation data, the ECU of the PV system was used. Figure 1 illustrates the process for the acquisition of electric power generation data.

Experimental procedures

The first step in the preparation of samples was to dry them to remove moisture, preparing them for sifting that would classify them in terms of granulometry.

The sedimentable particles are those that cross a sieve of 0.84 mm, where this value corresponds to the sieve mesh size (*Associação Brasileira de Normas Técnicas* [ABNT], 1991). Based on this definition and a study by (Santos et al., 2017), which found that the sedimentable particles had a diameter ranging from (5 to 100) μm , a 100 mesh aluminum sieve was used, equivalent to a mesh aperture of 150 μm , to perform the mechanical sieving of the samples.

The PM samples were dried, sieving, and weighed on an analytical balance and stored in glass containers. The amount of PM to be deposited in the experimental procedures was (0.00, 4.07, 8.15 and 16.3 g), determined as a function of the area of the photovoltaic modules (1.63 m^2), and of the desired dust mass surface density, (0.0, 2.5, 5.0, and 10.0) g m^{-2} .

Before each experiment, the modules were cleaned with detergent and plenty of water using a sponge, and then dried with cotton cloth, as recommended by (Sarver et al., 2013).

Then each module was uniformly 'polluted' by spraying water containing the selected pollutant and sufficient time was allowed for the sprayed water to evaporate and the operating temperature of each module to stabilize, according to the method used by (Kaldellis, Fragos, & Kapsali, 2011).

Figure 2 shows the result of the application of mineral coal powder on the modules. In this photograph one can see the different levels of dust on the PV modules.

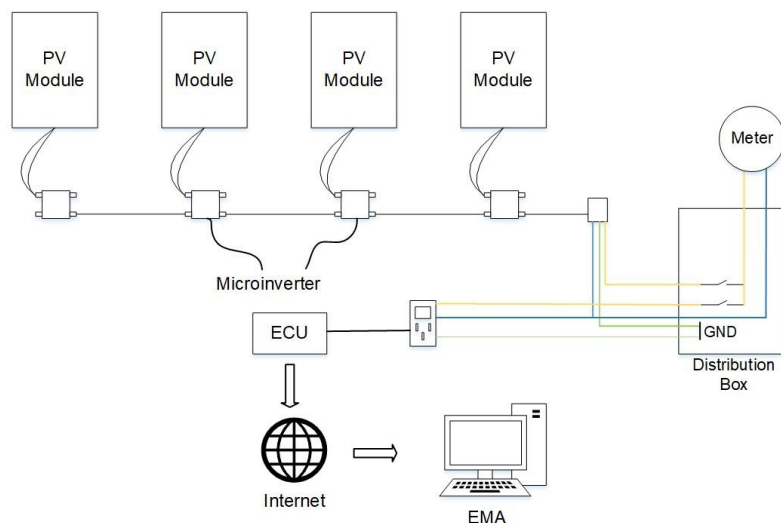


Figure 1. Flowchart of data acquisition of electric power generation.

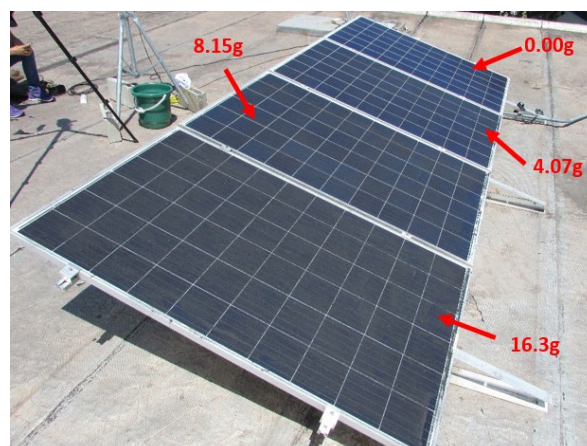


Figure 2. PV modules with application of mineral coal powder.

Although the experimental method does not require the measurement of meteorological variables, atmospheric temperature ($^{\circ}\text{C}$), relative humidity (%), wind velocity (m s^{-1}), and wind direction were measured by sensors installed in a Davis Vantage Pro2 meteorological station located near the photovoltaic system. The solar irradiance (W m^{-2}) was measured using a pyranometer model SP-2000. The data of the electric power generation (W) of each photovoltaic module were obtained through the APSystems' ECU real-time monitoring system, which has 1 W resolution. The individual temperature ($^{\circ}\text{C}$) of each PV module was recorded on the back of the modules using a recorder thermometer Minipa MT-1044, resolution of 0.1°C .

Particulate matter samples characterization

The characterization methods included particle sizing, morphological analysis, and chemical composition analysis (Said et al., 2018). Therefore, the collected samples were analyzed using a Scanning Electron Microscope (SEM) model EVO 10, brand Zeiss, to verify the effectiveness of the mechanical sieving and to analyze the chemical composition of the particles. The microscope images indicate that the particles were composed of different shapes and sizes ranging from (7 to 83) μm . The SEM was also used to analyze the particulate chemical elements of the PM samples. The results are presented on Table 1. The weight uncertainty has 99.7% confidence level. For all samples, it was found that their chemical compositions were compatible with typical compositions reported in surveys done in urban areas (Santos & Reis Jr., 2011).

PV modules characterization

In order to characterize the PV modules, the electrical power generated by each of the three experimental modules was initially obtained, relative to the reference module, in a per unit system (pu). PV module 01 was defined as reference (control model). Module 02 generates (0.999 ± 0.0023) pu; module 03, (1.018 ± 0.0023) pu; and module 04, (1.001 ± 0.0024) pu. These results are presented in mean and standard deviation format.

To express how correctly the measurement results represent the measured magnitude values the uncertainty of measurement concept (International Organization for Standardization [ISO] & International Electrotechnical Commission [IEC], 2008) is used.

To evaluate the measurement uncertainties in this research, the statistical concepts of the standard uncertainty approach of Type A presented in the Guide to the expression of uncertainty in measurement (GUM) were used (ISO & IEC, 2008).

The Central Limit Theorem states that when sample size is sufficiently large ($n > 30$), the sample distribution approaches a normal distribution (ISO & IEC, 2008; Montgomery & Runger, 2010). This theorem allows the application of statistical procedures that require the data to be approximately normal, as required by the hypothesis test.

Table 1. Chemical compositions of particulate matters.

Mineral Coal		Iron Ore		Building Construction		Quarry	
Atom	Weight/%	Atom	Weight/%	Atom	Weight/%	Atom	Weight/%
C	76.0 ± 0.1	Fe	38.9 ± 0.1	O	47.5 ± 0.4	O	46.2 ± 0.3
O	19.9 ± 0.1	O	36.0 ± 0.1	C	21.1 ± 0.6	C	21.3 ± 0.5
Si	1.4 ± 0.0	C	18.9 ± 0.2	Ca	14.1 ± 0.1	Si	13.3 ± 0.1
Al	1.1 ± 0.0	Al	2.5 ± 0.0	Si	8.2 ± 0.1	Al	5.2 ± 0.0
Fe	0.8 ± 0.0	Si	2.2 ± 0.0	Al	3.6 ± 0.0	Fe	3.7 ± 0.0
S	0.3 ± 0.0	Cu	0.9 ± 0.0	Mg	1.4 ± 0.0	Ca	3.3 ± 0.0
Ca	0.3 ± 0.0	Ca	0.4 ± 0.0	Cu	1.4 ± 0.0	K	2.1 ± 0.0
K	0.1 ± 0.0	Mg	0.2 ± 0.0	Fe	0.8 ± 0.0	Na	1.5 ± 0.0
Mg	0.1 ± 0.0	Ti	0.1 ± 0.0	S	0.5 ± 0.0	Cu	1.4 ± 0.0
				K	0.5 ± 0.0	Mg	1.4 ± 0.0
				Na	0.4 ± 0.0	Ti	0.3 ± 0.0
				Yb	0.2 ± 0.0	Ba	0.2 ± 0.0
				Ti	0.2 ± 0.0		
				Mn	0.1 ± 0.0		

Measured power correction

In order to mitigate the interference from weather variables such as solar irradiance, wind speed and relative humidity in the generating capacity results, the reference (one unit) and the experimental (three units) PV modules were installed with the same tilt angle and exposed to the same environmental conditions. Power measurements of the PV modules were taken simultaneously, when all PV modules were subjected to the same conditions. This procedure mitigates spurious variables' influence (Gonçalves Júnior & Sousa, 2018). Therefore, the only spurious variable to be taken in consideration was the operating temperature of each PV module.

In order to obtain the expected generated electric power, a reference temperature was set close to the operating temperature of the reference module, since the studies were comparative. The generated power was corrected as function of PV modules' temperature as recommended by their manufacture (Equation 1).

$$K_T = 1 + (C_T \cdot (T_m - T_{ref})) \quad (1)$$

where:

K_T is the temperature correction factor,

C_T is the PV module temperature coefficient obtained from its datasheet,

T_m is the measured operating temperature,

T_{ref} is the reference temperature used to normalize the temperatures of the PV modules.

A reference temperature was set close to the operating temperature of the reference module, since the studies were comparative. This procedure decreases the difference between the operating temperature of the modules and the reference temperature, reducing the errors and propagation of uncertainties.

Subsequently, the electrical power generated in pu of each of the experimental modules was calculated relative to reference module. Then, the corrected power was obtained for a reference temperature according to Equation 2, thus eliminating the influence of the operating temperature of the PV modules on the measured results.

$$P_C = P_m \cdot K_T \quad (2)$$

where:

P_m is the measured electrical power and P_C is the corrected power negating the interference from the module's own operating temperature, according Equation 3.

$$P_C' = \frac{P_C}{K_C} \quad (3)$$

After that, the generated powers were corrected according to the performed system characterization, expurgating the effects of any differences in construction between the parts of the system.

Finally, the mean and combined uncertainty of the generated power (P_C') by the experimental modules were computed.

The effect of PV modules temperature uncertainty on the measured electrical power output is insignificant as it would only affect the first decimal place and the power measured by the APsystems system is a non-decimal number. In quantitative terms, the uncertainty of the temperature instruments is of the order of 0.22%, while the uncertainty of the power measurements is of the order of 2.30%.

The electric power uncertainty obtained in Equation 3 is compounded by the standard uncertainty of the measured electrical power and the standard uncertainty of the PV modules characterization. These two uncertainties were combined as recommended by (ISO & IEC, 2008; Equation 4).

$$u_f^2 = \left(\frac{\partial f}{\partial x_1} \right)^2 \cdot u(x_1)^2 + \dots + \left(\frac{\partial f}{\partial x_n} \right)^2 \cdot u(x_n)^2 \quad (4)$$

Substituting the generic function f for the power of interest function in Equation 4, we have:

$$u_{P_c'}^2 = \left(\frac{\partial P_c'}{\partial P_c} \right)^2 \cdot u(P_c)^2 + \left(\frac{\partial P_c'}{\partial K_c} \right)^2 \cdot u(K_c)^2 \quad (5)$$

where:

u represents the combined uncertainty of the analyzed quantity.

In this paper, the expanded uncertainty of two standard deviations was used, that is, the reliability of the measurement is approximately 95%.

Result and discussion

Experiments results

For each PM analyzed; iron ore powder, quarry powder (grit), building dust and mineral coal powder; power was measured on the reference module (clean one) and on the three experimental modules, while under different surface deposition densities of (2.5, 5.0 and 10) g m⁻². Table 2 presents some of the 72 measured values of generated electrical power (P_m) and the operating temperature of each photovoltaic module (T_m) during the experiment carried out under mineral coal powder deposition.

From Table 2, it can be observed that the higher the superficial dust density, the lower the power generated. Table 3 shows some of the corrected electrical power (P_c) data under reference temperature (T_{ref}) of 46°C, according to Equation 1 and 2, where the C_T coefficient was 0.004 in accordance to PV modules datasheet. By comparing power data from Table 2 and 3, it is noted that the influence of the module temperature under the experimental conditions is not significant, being of the order of 1 W compared to the measured powers of the order of tens or hundreds of watts.

Table 4 presents the same data from Table 3, electrical power of each experimental module data, now in pu, considering module 01 as reference.

Table 2. Power generation and operating temperature of PV modules under mineral coal deposition - sample of data.

Reference Module (Clean)		#1 Experimental Module (2.5 g m ⁻²)		#2 Experimental Module (5.0 g m ⁻²)		#3 Experimental Module (10 g m ⁻²)	
Power (W)	Temperature (°C)	Power (W)	Temperature (°C)	Power (W)	Temperature (°C)	Power (W)	Temperature (°C)
222	46.4	177	49.8	149	48.7	101	49.0
196	44.4	159	47.4	131	46.5	89	47.8
230	46.2	186	49.9	155	49.0	107	50.5
237	47.1	192	51.4	160	50.3	111	52.0
238	48.1	193	52.3	161	51.0	111	51.2
242	47.5	196	50.1	164	49.4	114	50.4
247	48.2	200	51.9	167	50.4	116	51.7
248	48.1	202	51.6	170	50.4	117	51.6
251	49.0	204	51.7	171	50.5	119	52.0
253	49.9	206	53.3	173	51.1	120	52.4
255	51.5	208	54.5	175	52.6	123	53.9
263	52.0	214	55.9	179	53.9	125	66.7
257	52.8	210	55.8	177	54.1	124	55.2
256	52.6	209	56.3	176	54.6	123	56.2
266	52.0	217	55.5	182	53.6	127	56.0
250	53.1	207	56.8	175	54.7	124	57.0
264	52.8	215	56.6	181	54.7	127	57.0
265	54.3	217	57.2	182	55.9	128	58.4
271	52.8	224	55.9	189	54.3	132	56.5
272	54.1	227	58.6	191	56.5	133	58.8
148	49.8	125	51.8	103	49.8	71	52.4
260	50.8	227	53.9	192	52.7	134	54.1
258	54.0	220	57.0	185	54.5	128	57.3
211	51.9	182	55.9	153	54.7	109	56.3
179	46.6	157	50.3	136	48.3	85	50.9

Table 3. Corrected power generation, in watts, under mineral coal deposition, at reference temperature - sample of data.

Reference Module (Clean)	#1 Experimental Module (2.5 g m ⁻²)	#2 Experimental Module (5.0 g m ⁻²)	#3 Experimental Module (10 g m ⁻²)
222.4	179.7	150.6	102.2
194.7	159.9	131.3	89.6
230.2	188.9	156.9	108.9
238.0	196.1	162.8	113.7
240.0	197.9	164.2	113.3
243.5	199.2	166.2	116.0
249.2	204.7	169.9	118.6
250.1	206.5	173.0	119.6
254.0	208.7	174.1	121.9
256.9	212.0	176.5	123.1
260.6	215.1	179.6	126.9
269.3	222.5	184.7	135.4
264.0	218.2	182.7	128.6
262.8	217.6	182.1	128.0
272.4	255.2	187.5	132.1
257.1	215.9	181.1	129.5
271.2	224.1	187.3	132.6
273.8	226.7	189.2	134.3
278.4	232.9	195.3	137.5
280.8	238.4	199.0	139.8
150.2	127.9	104.6	72.8
265.0	234.2	197.1	138.3
266.3	229.7	191.3	133.8
216.0	189.2	158.3	113.5
179.4	159.7	137.3	86.7

Table 4. Power generation, in pu, under mineral coal deposition - sample of data.

Reference Module (Clean)	#1 Experimental Module (2.5 g m ⁻²)	#2 Experimental Module (5.0 g m ⁻²)	#3 Experimental Module (10 g m ⁻²)
1.000	0.808	0.677	0.460
1.000	0.821	0.674	0.460
1.000	0.821	0.681	0.473
1.000	0.824	0.684	0.477
1.000	0.824	0.684	0.472
1.000	0.818	0.683	0.477
1.000	0.822	0.682	0.476
1.000	0.826	0.692	0.478
1.000	0.821	0.685	0.480
1.000	0.825	0.687	0.479
1.000	0.825	0.689	0.487
1.000	0.826	0.686	0.503
1.000	0.827	0.692	0.487
1.000	0.828	0.693	0.487
1.000	0.827	0.688	0.485
1.000	0.840	0.704	0.504
1.000	0.826	0.691	0.489
1.000	0.828	0.691	0.491
1.000	0.837	0.701	0.494
1.000	0.849	0.709	0.498
1.000	0.851	0.696	0.485
1.000	0.884	0.744	0.522
1.000	0.863	0.718	0.502
1.000	0.876	0.733	0.525
1.000	0.890	0.765	0.483

This entire procedure was performed for the four soils studied.

Table 5 presents the averages of the generated electrical power (P_C), in pu, corresponding to each level of surface dust density with their respective standard uncertainty for each type of soil.

Table 6 presents the performed system characterization, eliminating the effects of any differences in construction between the parts of the system (K_C).

Table 7 shows the average electric power generated (P_C' corrected by the photovoltaic modules characterization factors (K_C) according to Equation 3, and the combined standard uncertainty of this power calculated from Equation 5, considering power measurement and characterization factor uncertainties presented in Table 5 and 6. It also presents the coefficient of variation and the combined expanded uncertainty with coverage factor 2, i.e. for a confidence level of approximately 95%. Although uncertainties are presented with three decimal places, rounding was performed only at the calculation of expanded combined uncertainty.

From Table 7, it is noted that the coefficient of variation varies from 2.8 to 8.5%, i.e., the combined standard uncertainties are lower than 10% of the measuring (generated power). It is classified as a weak to a medium level of variability (Calif & Soubdhan, 2016), demonstrating the good quality of the experimental data.

Discussion

Table 8 presents the averages of the electric power generated in pu corresponding to each dust density level of each dust with their respective expanded uncertainties in 95% confidence level. The statistical test Z was performed to find out the probability of each PV module generates more electric power than the immediately cleaner module. The column 'Z' presents the results. One can note that for Iron ore, Building construction, and Mineral Coal dusts, the dustier the PV module, the less the power generation, in a confidence level of at least 93%. For quarry powder, in a general way this conclusion is acceptable except for lower confidence levels for two cases (5.0 versus 2.5 g m⁻² and 10 versus 5.0 g m⁻²).

Table 9 presents the probability of the module with a particular dust type (row) generating more electric power than the module with each of the other dust types (column), under the studied densities level of dust deposition.

Table 5. Power generation, in pu, under each studied dust deposition.

Dust mass surface density	Iron ore	Building construction	Quarry	Mineral Coal
0.0 g m ⁻²	1.000	1.000	1.000	1.000
2.5 g m ⁻²	0.946 ± 0.024	0.926 ± 0.015	0.978 ± 0.018	0.816 ± 0.034
5.0 g m ⁻²	0.865 ± 0.036	0.874 ± 0.016	0.967 ± 0.019	0.675 ± 0.037
10 g m ⁻²	0.788 ± 0.047	0.777 ± 0.018	0.905 ± 0.025	0.462 ± 0.038

Table 6. Characterization factor of PV modules.

Experimental modules	Power/pu
Module 02	0.999 ± 0.023
Module 03	1.018 ± 0.023
Module 04	1.001 ± 0.024

Table 7. Generated power and their uncertainties, in pu.

Particulate Matter	Dust mass surface density	Power (Equation 3)	Power uncertainty (Table 5)	Characteriz. uncertainty (Table 6)	Combined standard uncertainty (Equation 5)	Coefficient of variation	Combined expanded uncertainty
Iron Ore	0.0 g m ⁻²	1.000	-	-	-	-	-
	2.5 g m ⁻²	0.947	0.024	0.023	0.033	3.44%	0.065
	5.0 g m ⁻²	0.866	0.036	0.023	0.041	4.72%	0.082
	10 g m ⁻²	0.774	0.047	0.024	0.049	6.32%	0.098
Building construction	0.0 g m ⁻²	1.000	-	-	-	-	-
	2.5 g m ⁻²	0.927	0.015	0.023	0.026	2.81%	0.052
	5.0 g m ⁻²	0.858	0.016	0.023	0.024	2.85%	0.049
	10 g m ⁻²	0.777	0.018	0.024	0.026	3.37%	0.052
Quarry	0.0 g m ⁻²	1.000	-	-	-	-	-
	2.5 g m ⁻²	0.979	0.018	0.023	0.029	2.93%	0.057
	5.0 g m ⁻²	0.950	0.019	0.023	0.028	2.97%	0.056
	10 g m ⁻²	0.903	0.025	0.024	0.033	3.63%	0.066
Mineral Coal	0.0 g m ⁻²	1.000	-	-	-	-	-
	2.5 g m ⁻²	0.817	0.034	0.023	0.039	4.75%	0.078
	5.0 g m ⁻²	0.663	0.037	0.023	0.039	5.96%	0.079
	10 g m ⁻²	0.462	0.038	0.024	0.039	8.50%	0.078

Table 8. Power generation under dust deposition.

Dust mass surface density	Iron ore		Building construction		Quarry		Mineral Coal	
	Power/pu	Z	Power/pu	Z	Power/pu	Z	Power/pu	Z
0.0 g m ⁻²	1.000	-	1.000	-	1.000	-	1.000	-
2.5 g m ⁻²	0.947 ± 0.065	0.000	0.927 ± 0.052	0.000	0.979 ± 0.057	0.001	0.817 ± 0.078	0.000
5.0 g m ⁻²	0.866 ± 0.082	0.066	0.858 ± 0.049	0.051	0.950 ± 0.056	0.228	0.663 ± 0.079	0.000
10 g m ⁻²	0.774 ± 0.098	0.065	0.777 ± 0.052	0.026	0.903 ± 0.066	0.125	0.462 ± 0.078	0.000

Table 9. p-values for test of hypotheses of different types and density of dust deposition.

Dust density (g m ⁻²)	Building construction			Iron ore			Quarry powder		
	2.5	5.0	10	2.5	5.0	10	2.5	5.0	10
Mineral coal	0.006	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000
Build. constr.	-	-	-	0.335	0.433	0.483	0.103	0.011	0.001
Iron ore	-	-	-	-	-	-	0.241	0.042	0.008

By analyzing results shown on Table 9, it can be concluded that the building construction, iron ore, and quarry powder dusts had less impact on electric power generation capacity than the mineral coal dust with a confidence level of at least 99%. By checking results that compare building construction and iron ore, their effects on power generation are similar. Quarry powder causes less impact on power generation than building construction dust with a confidence level at least 90%. In a similar way, quarry powder predominantly causes less impact than iron ore.

Conclusion

It was possible to experimentally quantify the different levels of attenuation of different dust compositions, the most significant reduction being caused by mineral coal dust; an average of 54% for 10 g m⁻² dust density.

The results obtained in this research are consistent with the results from other studies on PV modules power generation capacity reduction due to dust deposition. Studies that did not characterize the dust deposition indicate a capacity reduction of between (4 and 30)%. This research found capacity reduction from (2 to 54)% depending on density and type of dust.

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