ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.26, n.5, p.321-326, 2022
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v26n5p321-326

Dirt on photovoltaic modules and efficient energy generation in the Brazilian semiarid[1]

Sujidade em módulos fotovoltaicos e eficiência na geração de energia no semiárido brasileiro

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HIGHLIGHTS:

Rainless periods lead to dirt deposits on photovoltaic modules, decreasing their efficiency.
Fifteen rainless days is enough to considerably reduce the efficiency of photovoltaic modules in the Brazilian semiarid.
Rainfall above 1 mm can restore the output power of the photovoltaic modules in the semiarid region.

ABSTRACT: A photovoltaic electrical energy system is one of the least aggressive ways to affect the environment. Factors such as dirt influence the efficiency of these systems and can have a considerable impact in low rainfall regions, such as the Brazilian semiarid. In this respect, the aim of the present study was to analyze the effect of dirt on the efficiency of electricity generation in photovoltaic modules installed in the Brazilian semiarid. To that end, the output power of a periodically cleaned module was compared with a naturally dirty module; in addition, the percentage output power, dirt deposition density and relationship between these variables were estimated. The study was carried out at the University of Pernambuco, in the city of Petrolina, PE, Brazil, during dry and rainy periods. Data were collected via a data acquisition system and dirt using glass slides. The results indicate that more than 15 days without rain significantly reduces the efficiency of photovoltaic modules installed in semiarid areas, reaching an 18.72% decrease in output power after 70 days.

Key words: solar energy, environment, rainfall, output power

RESUMO: A geração de energia elétrica por sistemas fotovoltaicos é uma das formas menos agressivas ao meio ambiente. Fatores ambientais como a sujidade influenciam a eficiência desses sistemas, podendo impactar, consideravelmente, em regiões com baixo índice pluviométrico, a exemplo do semiárido brasileiro. Nesse contexto, o objetivo deste estudo foi analisar a influência da sujidade na eficiência da geração de energia elétrica em módulos fotovoltaicos instalados em área do semiárido brasileiro. Para isso, a potência de saída de um módulo limpo periodicamente foi comparada com um módulo naturalmente sujo e, por sua vez, o percentual de redução de potência, a taxa de deposição de sujidade e a relação entre a potência de saída e a taxa de deposição de sujidade foram estimados. O estudo foi realizado na Universidade de Pernambuco, na cidade de Petrolina, PE, abrangendo os períodos seco e chuvoso. A coleta de dados foi realizada por meio de um sistema de aquisição de dados e da distribuição de lâminas de vidro para coleta de sujeira. Os resultados indicam que períodos superiores a 15 dias sem chuva levam a reduções consideráveis na eficiência dos módulos fotovoltaicos instalados em áreas do semiárido, alcançando a redução de 18,72% na potência de saída, após 70 dias sem chuvas.

Palavras-chave: energia solar, meio ambiente, pluviosidade, potência de saída

• Ref. 253989 – Received 06 Jul, 2021
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• Accepted 26 Nov, 2021 • Published 27 Dec, 2021
Editors: Ítalo Herbet Lucena Cavalcante & Carlos Alberto Vieira de Azevedo

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Introduction

Photovoltaic solar energy has been growing worldwide, mainly in arid or semiarid regions, such as the Brazilian semiarid, since it is less aggressive to the environment and due to the region's high energy potential (Nascimento & Ruther, 2014; Gholami et al., 2018). The average solar irradiation of the Brazilian semiarid is 2174 kWh m^{-2} per year (Atlas Solar Global, 2020). However, environmental factors affect the efficiency of a photovoltaic system, including dirt, which is often neglected (Fraga et al., 2018; Gholami et al., 2018).

Dirt is a general term that applies to solid particles with diameters less than 500 μm deposited on the glass surface of photovoltaic modules, suspended in the atmosphere and originated from several sources (Ho et al., 2017; Fathi & Abderrezek, 2017). According to Fouad et al. (2017), dirt can prevent solar radiation from reaching the surface of photovoltaic cells, thereby reducing the energy generated.

A number of studies regarding the influence of dirt on the efficiency of photovoltaic modules have been carried out around the world. Appels et al. (2013), Radonjic et al. (2017) and Hachicha et al. (2019) investigated artificial dirt deposition. In a study of dirt on photovoltaic modules with an off-grid system, Paudyal & Shakya (2016) found a 29.76% decline in output power. The efficiency of naturally dirty solar panels was 11.5% lower than that of their clean counterparts in a California study (Caron & Littmann, 2013). Amarnadh et al. (2014) observed a maximum reduction of 30% in the efficiency of a polycrystalline silicon module in an experiment conducted in Vellore, India.

As such, this study aims to analyze the influence of dirt on the efficiency of electrical energy conversion in photovoltaic modules installed in the Brazilian semiarid by estimating the percentage decrease in output power, due to dirt deposition density, and the ratio between dirt deposition density and output power.

Material and Methods

The experiment was conducted in Petrolina, Pernambuco state, Brazil, located in the most populated semiarid region in the world (Cavalcanti, 2016), at latitude 09° 23' 55" S, longitude 40° 30' 03" W, and altitude of 376 m.

According to the Brazilian Institute of Geography and Statistics (IBGE, 2020), the Caatinga is the biome of the region, the climate is semiarid BSh (warm semiarid) according to Köppen's climate classification, with little rainfall, intense solar irradiation and high average temperatures.

The rainy season in Petrolina occurs between November and April (França et al., 2016). Average solar irradiation is around 5.77 kWh m^{-2} per day (CRESESB, 2014), resulting in a daily average of approximately five hours and 45 min of full sun. The region has also shown exponential growth in the number of photovoltaic plants installed, reaching 1360 systems and total installed power of more than 12.2 MW in June 2020 (ABSOLAR, 2021).

The experiment was carried out in the Laboratory of Physics and Renewable Energies of the University of Pernambuco, Petrolina campus, in the area of the campus exposed to the sun.

Based on the studies by Paudyal & Shakya (2016) and Hachicha et al. (2019), a data acquisition system was electronically implemented to measure the electrical quantities of the photovoltaic modules used in the experiment, and a support base built to install glass slides on the same slope and adjacent to the photovoltaic modules to collect dirt.

The experimental procedures, material and methods are presented below:

I) First, two 54 W KC50T KYOCERA photovoltaic modules produced at the same time by the same manufacturer were used to measure the electrical quantities. They were installed in a metallic structure on the facade of the building housing the Laboratory of Physics and Renewable Energies of the University of Pernambuco, with an inclination of 10° facing north and 0° azimuth, and connected to three parallel power resistors with a 15 ohm resistance and 20 W of power each. Red LEDs were connected in parallel in order to visualize the output power of the resistors in the photovoltaic system.

The electrical quantities (voltage, current and power) were collected via a data acquisition system and recorder (datalogger), equipped with an Arduino UNO microcontroller, voltage signal conditioning circuits and shields connected to the photovoltaic modules. The quantities measured were sent to a computer, along with their respective times and data readings taken every 2 s. One module was cleaned manually once a week using a moist cloth with no chemicals, while the other module remained naturally dirty in order to compare the efficiency of the two modules. The electrical quantity data were simultaneously collected in the clean and dirty module and saved on a memory card. Analysis was conducted between March 30, 2020 and November 30, 2020, covering the dry and rainy seasons.

It is important to note that the measurements on the clean and dirty modules were performed simultaneously under the same environmental conditions, using the same devices and underwent the same corrections in order to reduce uncertainties.

Rainfall was measured by a weather station installed on the university campus, 150 m from the experimental site. Additionally, rainfall was monitored to assess the output potential after 14 days with more than 1 mm (Figure 1).

Next, 100 rectangular 75 x 25 x 1 mm glass slides were used on a metallic structure adjacent to the modules, with the same inclination so that the particles deposited on the surface of the samples would have the same characteristics as those deposited on the module surface in order to estimate the dirt deposition density accumulated on the glass surface of the modules during the experimental period (Paudyal & Shakya, 2016).

All glass slides were numbered and weighed before the experiment. The accumulated dirt was collected weekly and submitted to quantitative analysis in the laboratory. The particles deposited on the surface of each glass slide were collected every seven days and the weight measured using a precision scale with 0.1 mg readability. Next, the accumulated weight was divided by the surface area of the sample to determine the accumulated dirt deposition density on the glass surface (mg m^{-2}). All slides were submitted to the natural

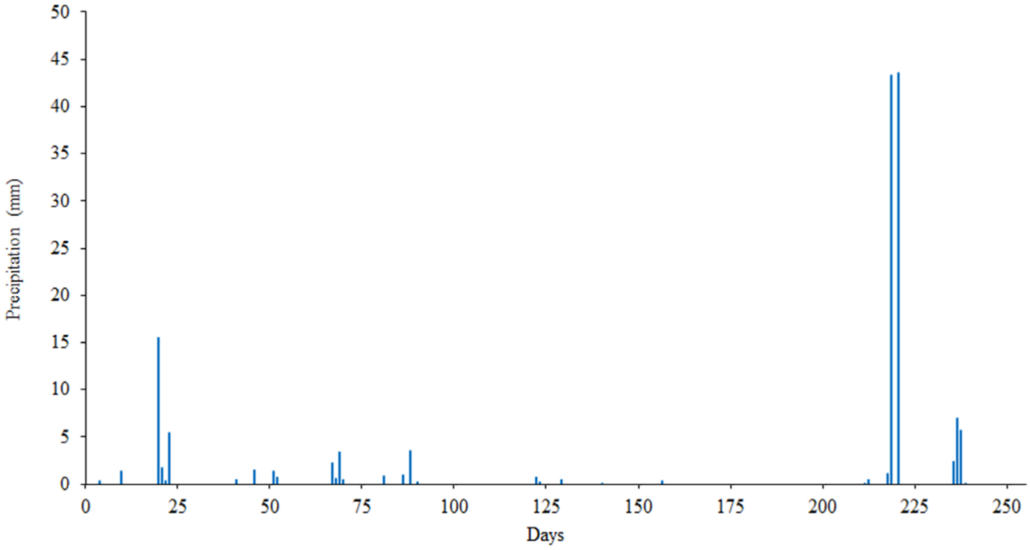


Figure 1. Rain distribution during the experimental period

effects of dirt and cleaning, meaning that no manual cleaning was carried out. Analysis was conducted for the same period as that of output power.

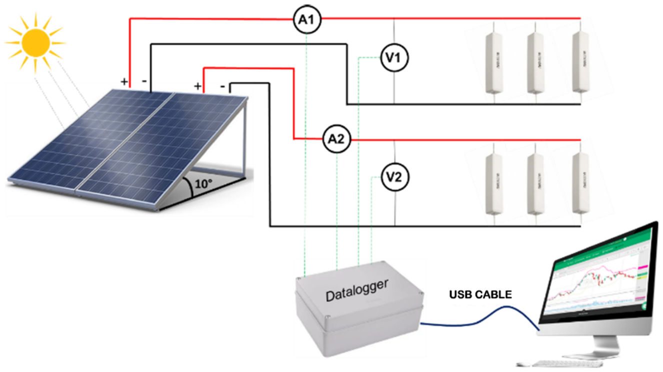
After that, dirt deposition and decline in output power were estimated, and the Pearson's correlation was determined between these two quantities to determine the effect of dirt on the output power of the modules. Figure 2 shows the experimental arrangement.

The percentage decline in output power (ΔP) was calculated according to Eq. 1, for the entire experimental period.

$$\Delta P = \left(\frac{P_c - P_d}{P_c} \right) 100 \qquad (1)$$

where:

P_c - output power of the clean module; and,
P_d - output power of the dirty module.



A1- Amperage meter 1; A2 - Amperage meter 2; V1 - Strain gauge 1; V2 - Strain gauge 2

Figure 2. Photovoltaic modules, data acquisition system and recorder (datalogger), Arduino microcontroller computer

Results and Discussion

Figure 3 presents the photovoltaic modules with accumulated dirt on the 177th day of the experiment, with Figure 3B showing a tendency towards a higher concentration of dirt particles at the bottom of the module, non-uniform distribution over its surface, and a higher concentration of dirt on the lower right side of the module than in other areas.

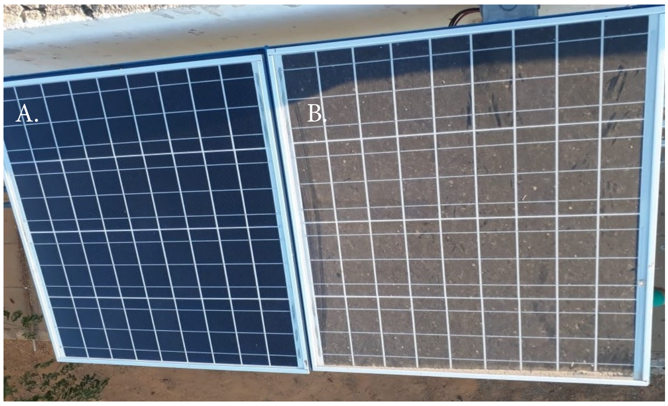


Figure 3. Photovoltaic modules - module cleaned weekly (A) and not cleaned, with accumulated dirt on the 177th day of the experiment (B)

Figure 4 exhibits the output power of the two modules during the experimental period. The comparison between the two modules in the first two months showed no significant reduction in the dirty module's output power. However, it began to decrease significantly starting in the dry period due to dirt accumulation on the module surface.

Figure 5 shows the reduced output power and dirt deposition density during the experimental period, demonstrating the effect of rain on the output power of the modules and the highly similar behavior of the variations in dirt deposition density and output power.

Figure 4 shows that the decline in output power of the dirty module in relation to its clean counterpart at the beginning of the experiment was practically null, since the beginning of the experiment coincided with a rainy period. However, as the experiment progressed to a rainless period, the output power of the dirty module gradually decreased due to dirt accumulation on the module surface or the greater dirt deposition density (Figure 5). These dirt-related reductions in output power are consistent with those found by Paudyal & Shakya (2016). In addition to rainfall, air temperature and relative air humidity and the tilt angle of the photovoltaic modules can contribute to reducing or increasing the percentage difference in power between the two modules, given that there is variation in this

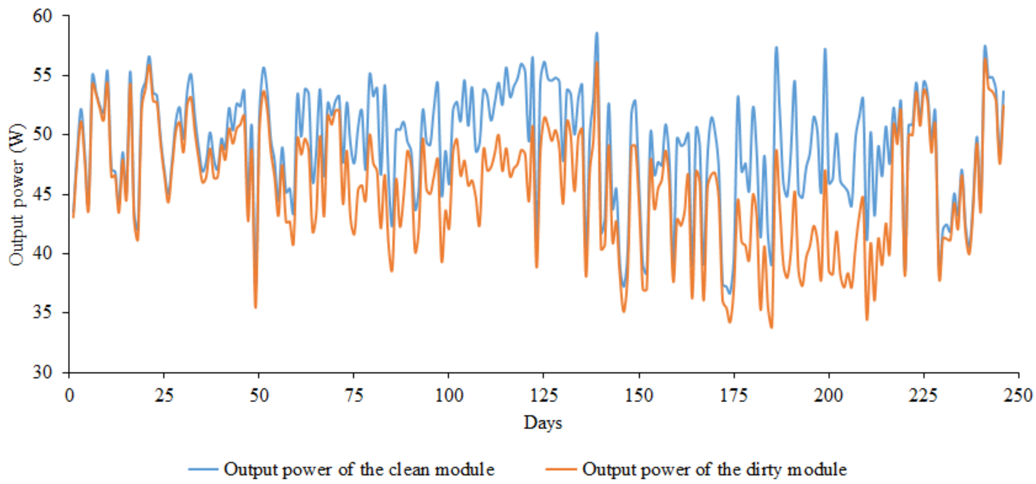


Figure 4. Output power of the two modules during the experimental period

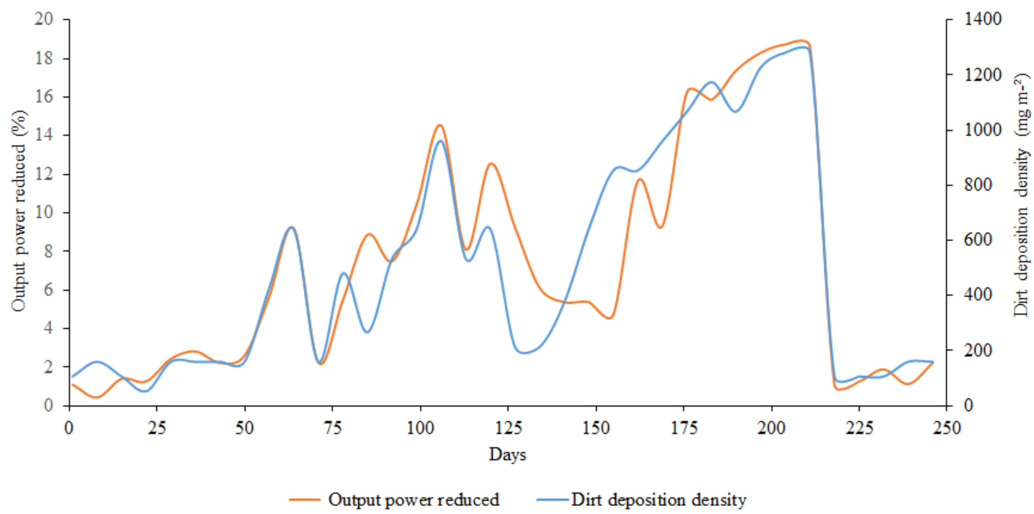


Figure 5. Reduced output power and dirt deposition density during the experimental period

magnitude, even in dry periods (Caron & Littmann, 2013; Hachicha et al., 2019).

Rainfall was significant in the region during the first 30 days of the experiment (Figure 1), totaling 25.1 mm in the first 41 days, thereby naturally cleaning the module surfaces. However, on the 65th day, 14 days after the last rainfall, a 10.98% decline in the dirty module's output power was observed. This was the first reduction above 10%, and suggests that rainfall with intervals shorter than 15 days can likely clean the modules.

Figure 5 shows a sharp drop in the reduced output power percentage in the final period of the experiment, which may be explained by the heavy rainfall that occurred on those days, accumulating 88 mm in just four days (Figure 1), which is more than enough volume to naturally clean the modules.

The highest percentage difference between the efficiency of the two modules occurred in a drought period, specifically on the 204th day of the experiment, with an 18.72% decrease 48 days after 0.3 mm of rain (Figure 5).

As reported by Hachicha et al. (2019), rainwater was able to clean the modules, as can be observed at some points in Figure 4 where output power stabilized. However, low rainfall (< 1 mm) was not sufficient to indicate significant changes in output power, suggesting that the module's dirt status did not change.

Hachicha et al. (2019) further report that humidity or low rainfall may contribute to the dirt problem, since they can form a cement layer on the module surface, a process known as cementation, which helps better adhere particles to the glass, making cleaning difficult and reinforcing the need to build a more complex model for residual dirt analysis.

After 0.1 mm of rain on the 141st day of the experiment, the photovoltaic module exhibited a deposit of residual natural dirt, as observed by Caron & Littmann (2013) in their work after low rainfall.

Figure 6 presents the dirty module on the 211th day after 0.1 mm of rain, showing the formation of a cement layer, non-uniform dirt distribution and residual dirt, which can contribute to reducing the output power of a photovoltaic module.

According to Nascimento & Ruther (2014), when dirt distribution is not homogeneous on photovoltaic module surfaces, in addition to losses related to reduced irradiance absorption, there are also losses due to electrical mismatch between the clean and dirty cells of the module. This can compromise module functioning as a whole due to partial shading, causing dirt to accumulate in a region of the module, which in turn, can cause power losses disproportionate to its area.

Figure 5 shows that soil deposition density is not constant for the period of the experiment, corroborating Gholami et al. (2018), who found a variation over time, with a period

Figure 6. Dirty photovoltaic module: non-homogeneous, cement layer and residual dirt

of greater or lesser deposition, depending on local weather conditions.

Dirt deposition density remained practically constant at the beginning of the study (Figure 5), possibly due to the rainy period during the first days of the experiment, which naturally cleaned the surfaces. Dirt deposition increased abruptly between the 134th and 204th days of the experiment, when the lowest accumulated rainfall occurred (0.4 mm). The highest dirt deposition density was 1280 mg m^{-2}, on the 204th day of the experiment, 48 days after a rainfall of only 0.3 mm.

According to Gholami et al. (2018), results can differ even in the same area under different climatic conditions. It is also noteworthy that the experiment was carried out during the COVID-19 pandemic, when there was a decrease in motor vehicle traffic and people mobility in the vicinity of the university campus. However, the results show reliable estimates of the dirt deposition trend on photovoltaic modules for areas in the semiarid region of Brazil.

After dirt deposition density and reduced output power were estimated, it was possible to relate the two quantities, as shown in Figure 7, which displays the scatterplot between the two variables. The Pearson's correlation coefficient (r) of 0.92 indicates that dirt deposition density is highly correlated with the decline in output power of the photovoltaic module, corroborating the studies by Paudyal & Shakya (2016) and Gholami et al. (2018).

Errors in dirt weight and electrical quantity measurements of the data acquisition system may have increased the distance between some points on the scatterplot (Figure 7). However, every measurement has an associated error, and the magnitude of the measurement error in the present study was minimal.

Points where small dirt deposition density values showed a considerable reduction in output power can be explained by the non-uniform distribution of dirt on the module surface, causing cell mismatch. Other environmental factors not investigated in this experiment, such as wind regime, physicochemical properties of dirt particles, relative air humidity and air temperature, may also have caused this discrepancy.

The highest dirt deposition density was 1280 mg m^{-2}, associated with an 18.72% decline in output power on the 204th day of the experiment.

Conclusions

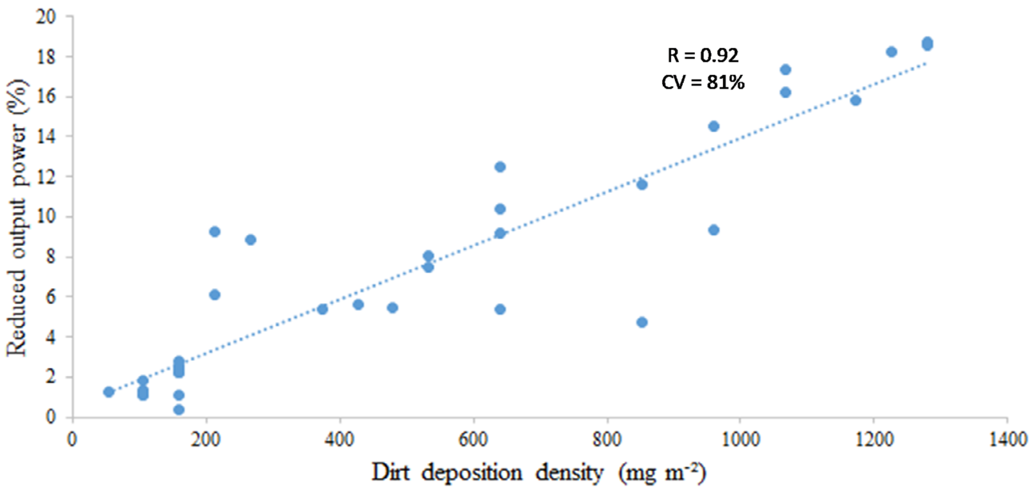
1. The naturally-deposited dirt on the surface of photovoltaic modules, in an area of the Brazilian semiarid, directly influences the efficiency of the modules, reducing their output power by 18% after 70 days without rain.

2. Rainfall above 1 mm was efficient in cleaning the modules and restoring the output power of the photovoltaic modules.

3. Cleaning the photovoltaic modules is recommended up to 15 days without rain in a semiarid region.

Acknowledgements

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for supporting the study – Funding code 001, and the Pós-Graduação em Ciências Ambientais and Programa de Tecnologia da Universidade de Pernambuco.



CV - Coefficient of variation

Figure 7. Correlation (r) between dirt deposition density and reduced output power of photovoltaic modules in the semiarid region

Literature Cited

ABSOLAR - Associação Brasileira de Energia Solar Fotovoltaica. Infográfico Absolar, 2021. Available on: <http://www.absolar.org.br/infografico-absolar.html>. Accessed on: Feb. 2021.

Amarnadh, G.; GUPTA, A.; SHYAM, V. Investigation of the Effects of Dust Accumulation, and Performance for Mono and Poly Crystalline Silica Modules. International Journal of Renewable Energy Research, v.4, p.628-634, 2014.

Appels, R.; Lefevre, B.; Herteleer, B.; Goverde, H.; Beerten, A.; Peasen, R.; Medts, K.; Driesen, J.; Poortmans, J. Effect of soiling on photovoltaic modules. Solar Energy, v.96, p.283-291, 2013. https://doi.org/10.1016/j.solener.2013.07.017

Atlas Solar Global - Global Solar Atlas. Available on: <http://www.globalsolaratlas.info/map>. Accessed on: Mar. 2020.

Caron, J. R.; Littmann, B. Direct monitoring of energy lost due to soiling on first solar modules in California. IEEE Journal of Photovoltaics, v.3, p.336-340, 2013. https://doi.org/10.1109/JPHOTOV.2012.2216859

Cavalcanti, L. C. de S. Geossistemas do Semiárido Brasileiro: Considerações Iniciais. Caderno de Geografia, v.26, p.214-228, 2016. https://doi.org/10.5752/p.2318-2962.2016v26nesp2p214

CRESESB - Centro de Referência para Energia Solar e Eólica. Manual de Engenharia para Sistemas Fotovoltaicos, Rio de Janeiro-RJ, 2014.

Fathi, M.; Abderrezek, M. Dust sensor based on luminescent glazing for control of photovoltaic panels cleaning. Clean Tech Environ Policy, v.19, p.1809-1814, 2017. https://doi.org/10.1007/s10098-017-1367-4

Fouad, M. M.; Shihata, L. A.; Morgan, E. S. I. An integrated review of factors influencing the performance of photovoltaic panels. Renewable and Sustainable Energy Reviews, v.80, p.1499-1511, 2017. https://doi.org/10.1016/j.rser.2017.05.141

Fraga, M. M. C.; Campos, B. L. de O.; Almeida, T. B. de; Fonseca, J. M. F. da; Lins, V. F. C. Analysis of the soiling effect on the performance of photovoltaic modules on a soccer stadium in Minas Gerais, Brazil. Solar Energy, v.163, p.387-397, 2018. https://doi.org/10.1016/j.solener.2018.02.025

França, M. V. de; Medeiros, R. M. de; Holanda, R. M. de; Rolim Neto, F. C.; Correa, M. M.; Silva, V. de P. Climatologia da precipitação em Petrolina - PE, Brasil. Revista Workshop Internacional sobre Água no Semiárido, p.7-11, 2016.

Gholami, A.; Khazaee, I.; Eslami, S.; Zandi, M.; Akrami, E. Experimental investigation of dust deposition effects on photo-voltaic output performance. Solar Energy, v.159, p.346-352, 2018. https://doi.org/10.1016/j.solener.2017.11.010

Hachicha, A. A.; Al-Sawafta, I.; Said, Z. Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions. Renewable Energy, v.141, p.287-297, 2019. https://doi.org/10.1016/j.renene.2019.04.004

Ho, C. K.; Christian, J. M.; Romano, D.; Yellowhair, J.; Siegel, N.; Savoldi, L.; Zanino, R. Characterization of particle flow in a free-falling solar particle receiver. Journal of Solar Energy Engineering, Transactions of the ASME, v.139, p.1-9, 2017. https://doi.org/10.1115/1.4035258

IBGE - Instituto Brasileiro de Geografia e Estatística. Available on: <https://cidades.ibge.gov.br/brasil/pe/petrolina/panorama>. Accessed on: Feb. 2021.

Nascimento, L. R. do; Ruther, R. A avaliação de longo prazo de um sistema fotovoltaico integrado à edificação urbana e conectado à rede elétrica pública. Revista Brasileira de Energia Solar, v.5, p.73-81, 2014.

Paudyal, B. R.; Shakya, S. R. Dust accumulation effects on efficiency of solar PV modules for off grid purpose: A case study of Kathmandu. Solar Energy, v.135, p.103-110, 2016. https://doi.org/10.1016/j.solener.2016.05.046

Radonjic, I. S.; Pavlovic, T. M.; Mirjanic, D. L.; Radovic, M. K.; Milosavljevic, D. D.; Pantic, L. S. Investigation of the impact of atmospheric pollutants on solar module energy efficiency. Thermal Science, v.21, p.2021-2030, 2017. https://doi.org/10.2298/TSCI160408176R