Influence of dust deposition, wind and rain on photovoltaic panels efficiency in Arequipa – Peru

Stamber Alvaro Ramírez-Revilla, Juan José Milón Guzmán, Karim Navarrete Cipriano and Sergio Leal Braga

ABSTRACT

The present study the influence of dust, wind and rain on the performance of a photovoltaic was evaluated. To determine efficiency of panels influenced by external factors, a system was designed and installed, voltage, electric current, solar irradiance and temperatures were measured. Three types of dust were used to simulate the atmospheric dust; cement, ashlar and clay. Parameter considered for deposition of the powders was surface density (g/m²). Particle size was determined by granulometry, samples were analyzed by SEM/EDS. For the wind factor, three speeds were determined within a range of average speeds recorded in urban areas, tests were carried out in natural rain conditions. Results show that 06:00 a.m. to 5:30 p.m. energy generation efficiency of panels decreases due to increase of dust deposition. As well, it is shown that influence of wind increases efficiency slightly and that the performance of panels is directly influenced in rainy conditions.

1. Introduction

In order to meet the ever-increasing demand for electricity around the world, photovoltaic systems are being used to convert solar energy into electricity (Charf et al. 2018). Using photovoltaic cells to convert sunlight into electricity is a clean and sustainable way of producing energy. The predominant solar technology uses crystalline silicon (polycrystalline and monocrystalline) as a semi-conductor material (Mussard and Amara 2018).

The performance of photovoltaic systems is affected by internal and external factors, such as weather conditions, structural characteristics, aging, shade, ambient temperature, heat and fluid velocity, radiation, wind, pollution, dust and cleanliness, as well as the intensity of solar radiation and it is of vital importance to consider these factors when implementing a photovoltaic installation (Hussain, Batra, and Pachauri 2017; Kumar SIngh et al. 2019; Salari and Hakkaki-Fard 2019; Cheema, Shaaban, and Ismail 2021). In the United Arab Emirates, the effect of dust on photovoltaic performance was thoroughly researched. Powder characterisation and a comparison between indoor and outdoor experiments were studied to arrive at a correlation between dirt loss and the degradation of photovoltaic performance (Amine Hachicha, Al-Sawafta, and Said 2019). Wind also plays an important role in dust deposition and its removal from the photovoltaic solar module surface, the rate of dust deposition depends on the amount of dust carried in the air and its speed (Gupta et al. 2019).
The output power generated by a photovoltaic system is estimated by manufacturers under standard test conditions (STC) in which the module is tested at a temperature of 25°C, an air mass of 1.5 and a solar radiation of 1000 W/m². However, these conditions are different from those of outdoor exposure, so it is essential to analyze the meteorological parameters that can affect the performance of these systems (Maftah and Maaroufi 2019).

While the use of photovoltaic energy is increasing, there are various technical and environmental problems that limit the capacity to obtain the optimal performance of photovoltaic panels. One of the main problems is the deposition of dust on the surface of the photovoltaic panel (Syafiq et al. 2018). Several studies have evaluated the effect of dirt on photovoltaic panels, showing a reduction in the performance or efficiency of the systems for a certain period of time. There is no direct correlation between the reduction in the system’s efficiency and exposure time because this factor depends on the location, contamination levels and amount of dust or dirt accumulated (Mehmood, Al-Sulaiman, and Yilbas 2017; El-Shobokshy and Hussein 1993). Energy losses have been found to increase by up to 80% in some places, especially in the Sahara and other deserts due to the effect of dust (Kazem et al. 2020). In order to ensure the high performance of the panels, a self-cleaning mechanism is recommended according to the geographical region and climatological characteristics (Memiche et al. 2020).

Some articles have evaluated the performance of photovoltaic systems using clay and evaluating the physical properties of different dust particles (cement, limestone, carbon), demonstrating that dirt has an influence on the decrease in performance of photovoltaic panels (Mehmood, Al-Sulaiman, and Yilbas 2017; El-Shobokshy and Hussein 1993; Mastekbayeva and Kumar 2000; Arroyo Fernández 2010).

Air, humidity and temperature, in addition to wind speed, play an important role in defining the insulated dust and how it will accumulate on top of the photovoltaic cell (Hussain, Batra, and Pachauri 2017). The surface temperature and the performance of photovoltaic cells are affected by the wind since it can cause temperature variations within the photovoltaic modules (Goverde et al. 2015).

Various experiments carried out in wind tunnels have analyzed the effect of wind speed on the performance of photovoltaic cells, showing that, for example, drops in performance due to dust accumulation are greater as the wind speed increases (Goossens and Van Kerschaeiver 1999). Moreover, wind speed plays a role in efficiency variations for differently mounted modules, as shown by an article that evaluated two photovoltaic modules (monocrystalline and polycrystalline silicon) under controlled conditions in a wind tunnel in the presence of an artificial solar simulator (Ali et al. 2017). Furthermore, different wind speeds and attack angles were applied to a ground-mounted photovoltaic panel in a wind tunnel, tested at 15° and 23° inclinations in open terrain (López, Parnás, and Cataldo 2019). Another study evaluated photovoltaic panels installed on roofs of buildings and it was determined that wind, temperature and electrical performance patterns are considerably affected by the panel’s set-up. Although better ventilation does not automatically guarantee higher electrical performance, since, in most photovoltaic modules, the cells are connected in series and the operating temperature mainly influences the open circuit voltage of the entire module, thereby letting the output power be determined by the behaviour of each individual cell (Goossens, Goverde, and Cathoor 2018).

Studies show that in rainy periods, water cleans the dusty modules and restores their normal performance. Even light rains are enough to clean the panel, reducing the amount of dust accumulated. However, during long periods without rain, like summer, dust accumulation decreases the panel’s performance (Zorrilla-Casanova et al. 2011). The amount of rain required for a full recovery of the module’s performance in intense agriculture areas is 0.5 mm (Caron and Littmann 2012). In addition, other studies show that rain can have non-negligible benefits on the yields of photovoltaic systems. In spring/summer periods, the first benefit is related to the strong reduction of thermal losses due to sensitive and evaporative cooling, while the second advantage is related to the reduction of reflection losses thanks to the presence of a thin layer of water on the photovoltaic glass (Del Pero, Aste, and Leonforte 2021).
Scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDS) is a useful technique to determine the morphology and chemistry of various materials and individual particles (Wagner et al. 2013). The applicability of SEM/EDS for the characterisation of different dust samples has been demonstrated in recent studies which have analyzed environmental dust (Webster et al. 2009), antimony and bromine presence in high impact polystyrene polymers (Holbrook et al. 2012), the water content in powder derived from cement kilns (Czapik et al. 2020), the composition of demolished materials and the risks they represent to health (Oliveira et al. 2019), among others. In the United Arab Emirates, the characteristics of five types of powder of C, Fe$_2$O$_3$, MnO$_2$, CaO and natural powder were evaluated (Darwish, Sopian, and Fudholi 2021). Other studies investigated the physicochemical characteristics of the dust accumulated in panels through FE-SEM analyses, showing the irregularity of the dust particles (Ali Sadat et al. 2021). Others used various analytical techniques like UV-Vis, XRD, FTIR, SEM and EDS spectroscopy, which provided structural and elemental analyses of the dust, demonstrating that dirt and dust accumulation have an important effect on the transmittance of the evaluated glass plates (Dhaouadi et al. 2021).

The Arequipa region in Peru has a varied climate due to the different geographical areas that make up its territory. The region has an arid, temperate climate (mountains) and a mild, cloudy climate on the coast. Heavy precipitations increase from November to March, which reduces the amount of dust particles that accumulate in photovoltaic panels whereas light rain affects their performance by favouring the adhesion of these particles to the panel. In the city of Arequipa, three sources of dust particles that can accumulate in panels as a form of dirt have been identified, among which we have cement, ashlar (volcanic stone) and clay (from brick production).

The objective of the present study is to evaluate the efficiency of photovoltaic panels in Arequipa through the influence of wind, rain and the accumulation of dust particles of cement, ashlar and clay. The chemical composition of the dust was analyzed with scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM / EDS).

2. Materials and methods

2.1. Photovoltaic module

For the experiment, two new monocrystalline photovoltaic panels (same manufacturing batch) were used. Table 1 details the technical specifications of the panels according to the manufacturer. Both panels were tested before the experiment (open circuit voltage – Voc and short circuit – Isc) to ensure optimum performance.

Both photovoltaic panels were placed on the roof of a building, with no shade, facing north and with an inclination of 0°, which guaranteed homogeneity in dust accumulation. A reference panel (kept always clean) and a test panel (with dust accumulation, under the influence of wind and rain) were used.

For the determination of the electrical load, each of the photovoltaic panels fed an electrical load of 130 W (maximum power) in 24 V in direct current.

| Parameter | Value |
|-----------|-------|
| Brand, model | Intipower, CYC90-12 |
| Maximum power in STC* ($P_{max}$) | 90 W |
| Open circuit voltage ($V_{oc}$) | 21.2 V |
| Short circuit current ($I_{sc}$) | 5.86 A |
| Maximum power voltage ($V_{mp}$) | 17.2 V |
| Maximum power current ($I_{mp}$) | 5.23 A |
| System’s maximum voltage | 600 V DC |
| Area | 0.648 m$^2$ (1200 mm x 540 mm) |

*STC: 1000 W/m$^2$, AM1.5, 25°C.
The measurement of solar irradiance on the photovoltaic panels was performed using a pyranometer (Model SP-110-SS; Sensitivity of 0.2 mV W/m²; Brand: Apogee Instruments) that measured the global irradiance.

The electric current was determined with a current metre that works with a Hall effect sensor (Model ACS712ELCTR-20A-T; Sensitivity of 100 mV/A; Arduino), connected to the data acquisition system (DAS) (Model 34972A LXI Data Acquisition/Switch Unit; Keysight Technologies), which allowed the acquisition of current, voltage, resistance, frequency and temperature RTD signals.

Temperature was measured using Teflon-coated 0.1 mm diameter K-type thermocouples. Uncertainties were calculated using the Kline McClintock method (Moffat 1988) (Table 2).

The photovoltaic panels were exposed to solar radiation (Figure 1). The tests were carried out from October 2018 to March 2019 from 06:00 a.m. to 05:30 p.m. to obtain representative results.

2.2. Dirt factor evaluation

The dust or dirt deposited on the surface of the PV panels was characterised by its density (g/m²) and its particle size (Arroyo Fernández 2010). The determination of the effect of dirt on efficiency depends on the location, that is, it is related to the environmental pollution of the air in the studied area, therefore, it is not possible to generalise a type of dirt for all cases (Kaldellis and Kapsali 2011). Different places can have different types of particles suspended in the atmosphere, and this can have an effect in the reduction of the solar radiation that reaches the panels (Conceição et al. 2018).

The main sources of air pollution in the city of Arequipa come from activities such as brick and cement production and ashlar quarries. In brick production, clay is generally used as a raw material (Alvarez-Rozo et al. 2018), cement is the main element used in urban buildings and is present in the air in different concentrations (Arroyo Fernández 2010) and ashlar, material of volcanic origin, traditional in Arequipa’s architecture, is extracted from several quarries where they are also cut and carved, generating fine ashlar particles found in the environment due to wind (Ruís Bueno et al. 2014). Concerning photovoltaic panels’ efficiency, studies determined that if the dust particles are smaller, the efficiency losses are greater, due to their uniform distribution or deposition on the surface of the panel, therefore, the light that can attain the cells is less than for larger particles deposits (Abderrezek and Fathi 2017). According to the literature, the size of particles in the atmosphere varies between 1 and 100 µm.

| Parameter               | Unit   | Uncertainty (%) | Reference   |
|-------------------------|--------|-----------------|-------------|
| Solar irradiance        | W/m²   | ± 0.5           | Instrument  |
| Area                    | M      | ± 0.3           | Instrument  |
| Electric current        | A      | ± 0.5           | Instrument  |
| Voltage                 | V      | ± 0.1           | Instrument  |
| Temperature             | °C     | ± 2.5           | Instrument  |
| Wind speed              | m·s⁻¹  | ± 3             | Instrument  |
| Solar power             | W      | ± 0.6           |             |
| PV Electric power       | W      | ± 0.5           |             |
| PV Electric efficiency  | W/W    | ± 0.8           |             |

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Based on the previously explained arguments, clay, cement and ashlar dust samples were used. The size of these dust samples was less than <75 µm. To determine the particle size of the powders, ASTM C 136 – 01 ‘Standard Test Method for analysis of fine and coarse aggregates through sieving’ and ASTM C 117 – 95 ‘Standard Test Method for material finer than No. 200 mesh (75 µm) in mineral aggregate through washing’ were reviewed. For particle size analyzes, a quantity of powder was added to a No. 200 mesh screen (75 µm) and stirred manually. The collected powder was used for the study.

A Quattro S Thermo Scientific Scanning Electron Microscope (SEM) with UltraDry Thermo Scientific Energy Dispersive Spectroscopy Detector (EDS) was used to perform an image characterisation and determine the morphology and the chemical composition of the powder under study.

The indicator that best reflected the deposition of dust accumulated on a panel was the surface density (g/m²) (El-Shobokshy and Hussein 1993; Arroyo Fernández 2010). In accordance with what was reviewed, 5, 15, 25 and 35 g/m² densities were selected, the surface area of the panels under study was determined, as well as the amount of each powder that would be used (<75 µm). Subsequently, each type of powder was placed manually, using around a 1 m high cardboard cover around the panel which prevented the loss of dust. The suspended particles were deposited on the surface of the photovoltaic panel by the effect of gravity (Figure 2).

### 2.3. Wind factor evaluation

The evaluation of the effect of the wind was carried out using an industrial fan with three power settings (52, 58 and 73 W). To homogenise the wind speed and to distribute it evenly on the panel, a cover was placed around the fan (Figure 3). The wind speed generated by each fan power level was measured using an anemometer. The wind speeds were 3.6, 3.9 and 4.1 m/s, respectively.
2.4. Rain factor evaluation

The evaluation of the effect of rain was carried out under natural rain precipitation conditions. Rain affected the performance of the photovoltaic panel during energy production since clouded skies generally cause a drop in solar irradiance.

3. Results and discussion

3.1. Preliminary performance tests

Figure 4 shows the comparison of efficiency for both clean panels. The efficiency of the reference and test panels was very similar: the maximum efficiency was 11%. The results are shown for a typical summer day in the city of Arequipa (November–December), during which the maximum solar irradiation (11:48 h) reached values of 1001 W/m².

3.2. Dirt factor test

In the present study, the particle size of the clay dust, ashlar and cement samples was determined (<75 μm) through granulometry. Subsequently, the samples were prepared and analyzed using scanning electron microscopy and energy dispersed spectroscopy (SEM/EDS) for image
characterisation and morphology and chemical composition determination. The results obtained for each of the powders (clay, ashlar and cement) are shown in Figures 5–7, respectively.

Figures 5–7 show the EDS spectra and SEM micrographs of the samples. The figures indicate that the dust particles are made up of elements of different shapes and sizes. The approximate diameter of each one is much less than 75 µm.

Figure 8 shows the results of SEM/EDS, where the composition (in %) of the powders is shown. It was found that for clay powder, carbon, oxygen, silicon and aluminium predominated, for characterisation and morphology and chemical composition determination. The results obtained for each of the powders (clay, ashlar and cement) are shown in Figures 5–7, respectively.

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Figure 8 shows the results of SEM/EDS, where the composition (in %) of the powders is shown. It was found that for clay powder, carbon, oxygen, silicon and aluminium predominated, for
cement, carbon, oxygen, silicon, calcium and aluminium concentrations were the most important, and for the ashlar, carbon, oxygen, silicon, aluminium and sodium were more present. The results coincide with percentages determined in previous studies (Shao et al. 2019; Aliabdo, Abd-Elmoaty, and Hassan 2014; Gallegos Florez 2012).

After performing several efficiency tests for the types of powder under study, the established dust deposition (surface density) of 5, 15, 25 and 35 g/m², the efficiency of the reference panel (Pr) and the test panel (Pp) was compared. Figure 9 shows that, for a 5 g/m² surface density of ashlar (<75 µm), there was a slight decrease from a maximum efficiency of 10.8% (clean panel) to 9.4% (dirty panel).

Figure 10 shows the variation in efficiency with different materials (clay powder, ashlar and cement) in different surface densities (<75 µm). It is observed that the efficiency does not depend on the type of particle, this is because the dust particles cause the same decrease in efficiency. The results show the importance of cleaning and maintaining photovoltaic panels, mainly in areas where environmental factors increase the adhesion of these particles on the panel surface.

### 3.3. Wind factor tests

Figure 11 shows the performance results of the photovoltaic panel with different wind speeds at the same ambient temperature. It is observed that increasing the wind speed slightly affects the efficiency (Ali et al. 2017). It is also observed that, for the city of Arequipa, the wind speed is not a lever for efficiency improvement since, in urban areas, speeds do not exceed 4 m/s.
Figure 12 shows the temperatures on the panels for a wind speed of 4.1 m/s. Temperature number 2 corresponds to the part exposed to the sun and temperature number 1 corresponds to the bottom of the panel. The reference panel shows higher temperature values than the wind-cooled panel: the cooling process reduces the panel temperature by up to 20°C. Literature indicates that temperature reduction improves the useful life of photovoltaic panels. In the case of the panel air-cooled by forced convection, it was observed that the temperature of the surface exposed to the sun was lower than the one of the lower surface of the panel. It can be deduced that the convection effects are of greater importance on the upper surface. Even though the test was carried out several times showing the same results, these values fall within the uncertainty of the temperature sensors, it could thus be assumed that the temperature in the upper and lower part of the panel are very similar.

3.4. Rain factor test

Rain affects the performance of photovoltaic panels directly. The experiments to evaluate the influence of this factor were carried out during the rainy season in Arequipa. Despite having studied several cases, in all of them, the appearance of rain implies extreme cloudiness that causes a drastic
drop in solar radiation. In Figure 13, it is observed that since the rain starts at 14:24 h, the solar radiation falls drastically from approximately 800 W/m² to a value lower than 100 W/m². The voltage and current fall to almost zero, consequently, the electrical power falls as well.

Despite the fact that the rain phenomenon reduces the solar radiation that attains the panels, solar radiation is not reduced to zero, since there is still visibility.

In Figure 14, the variation of the temperature under the effects of rain is observed. Before the rain begins, the temperatures were approximately between 30°C and 40°C, when it started to rain, the solar radiation fell and temperatures gradually decreased to stabilise at ambient temperature. Under these conditions, there was no electricity production.

In Figure 15, the variation in energy efficiency in the presence of rain is observed. Solar radiation falls drastically and consequently, the efficiency decreases to almost zero. Despite the fact that the rainy weather conditions improve the temperatures due to the cooling, solar radiation, which is in charge of the electricity production decreases. In the presence of rain, electrical production is neglectable.
4. Conclusions

The present research study was carried out in the city of Arequipa. The impact of the accumulation of clay, ashlar and cement dust particles, typical in the region, was evaluated, as well as the influence of wind and rain on the performance of photovoltaic panels. Two new monocrystalline photovoltaic panels were used: a reference panel and a test panel, both located in an exterior environment during the months of the study. Before starting the tests, their efficiency was evaluated, proving to be very similar.
The particle size of the clay, ashlar and cement dust samples was determined by granulometry and analyzed by scanning electron microscopy and energy dispersed spectroscopy (SEM/EDS). The SEM microphotographs showed that the dust particles have different shapes and size and the EDS spectra indicated the chemical composition of the types of powder, which turned out to be similar to what had been reported by other studies.

The efficiency of the photovoltaic panel increases slightly when forced convection is applied, since it reduces the panels’ operating temperature, but the increase in efficiency is not significant enough to be applied in installations. The photovoltaic panel’s efficiency is drastically reduced in the presence of rain due to the cloudiness and hence, low radiation. Moreover, the efficiency is reduced due to the influence of dirt, showing that it is important to maintain the panels clean. When a panel is naturally ventilated, there is an increase in its efficiency, but if forced convection is applied, the efficiency decreases, and energy production costs would increase. Finally, in rainy conditions, the efficiency of photovoltaic solar energy decreases, therefore, the production of electrical energy is scarce.

**Availability of data and materials**

All data generated or analyzed during this study are included in this published article.

**Authors’ contributions**

Stamber Alvaro Ramírez-Revilla carried out sample preparation, methodology, supervision and editing. Juan José Milón Guzmán conducted visualisation and data curation. Karim Navarrete Cipriano conducted laboratory experimental studies and validation. Sergio Leal Braga critically reviewed the final version and contributed to project administration. All authors read and approved the final manuscript.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).
Funding

This research study was funded by the CYTED Network – Solar energy storage for isolated communities (RED CYTED – 717RT0535 – ALMACENAMIENTO DE ENERGÍA SOLAR PARA COMUNIDADES AISLADAS – AESCA).

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