Influence of Dust Deposition, Wind and Rain on Photovoltaic Panels Efficiency in Arequipa - Peru

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Research

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Abstract

Photovoltaic solar technology is undergoing remarkable progress and occupies an important place among the most used renewable energies. In the present study, the influence of dust, wind and rain on the performance of a photovoltaic system operating in Arequipa - Peru was evaluated. To determine the efficiency of photovoltaic panels influenced by external factors, a photovoltaic system was designed and installed, voltage, electric current, solar irradiance and temperatures were measured. For the dirt tests, three types of dust were used to simulate the atmospheric dust of the city: cement, ashlar (volcanic stone) and clay dust were used. The parameter considered for the deposition of the powders on the panels was surface density (g/m2). The particle size was determined by granulometry, the samples were analyzed by scanning electron microscopy and energy dispersive spectroscopy (SEM / EDS), obtaining spectra, microphotographs and chemical composition.

For the wind factor, three speeds were determined within a range of average speeds recorded in urban areas, and tests were carried out in natural rain conditions. The results show that from 06:00 a.m. to 5:30 p.m. the energy generation efficiency of the photovoltaic panels decreases due to the increase of dust deposition. As well, it is shown that the influence of the wind increases efficiency slightly and that the performance of photovoltaic panels is directly influenced in rainy conditions.

1. Introduction

Nowadays, photovoltaic systems that convert solar energy into electricity [1] are being used to meet the growing demand for electricity worldwide. Using photovoltaic cells to convert solar energy into electricity is a clean and sustainable way of producing energy. Predominant solar technologies use crystalline silicon (polycrystalline and monocrystalline) as a semiconductor material [2].

The performance of photovoltaic systems is affected by internal and external factors, such as weather conditions, solar radiation, temperature, wind speed, wind direction, structural characteristics, aging, shades, pollution, dust, and cleanliness; it is thus of vital importance to consider these factors when implementing a photovoltaic installation [3,4].

The power generated by a photovoltaic system is estimated by manufacturers under standard test conditions (STC), which require the module to be tested at a temperature of 25°C, with an air mass at a spectral distribution of AM1.5 and an irradiance of 1000 W/m2. However, these conditions are different from those the module will be exposed to in the outdoors, therefore, it is essential to analyze the external parameters that can affect the performance of these systems [5].

Several technical and environmental problems limit the capacity of obtaining maximum power from photovoltaic panels. One of the main problems is the deposition of dust on the surface of photovoltaic panels [6]. Different research studies have evaluated the effect of dirt on photovoltaic panels, showing that there is no direct correlation between the reduction in the system’s efficiency and exposure time, because this factor depends on the location, pollution levels and amount of dust or accumulated dirt [7,8].

Some articles have evaluated the performance of photovoltaic systems using clay, evaluating the physical properties of different dust particles (cement, limestone, carbon), demonstrating that dirt has an influence on the decrease of photovoltaic panels performance [7–10]. Air, humidity and temperature, besides wind speed, play an important role in defining isolated dust and the way it will accumulate on top of the photovoltaic cells [3].

The surface temperature and the performance of photovoltaic cells are affected by the wind, since it can cause temperature variations within the photovoltaic modules [11]. 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 wind speed increases [30], 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 [25]. 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 an open terrain [12]. Another study evaluated photovoltaic panels installed on building roofs. It determined that wind, temperature and electrical performance patterns are considerably affected by mounting, 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, therefore letting the output power be determined by the behavior of each individual cell [26].

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. The amount of rain required for full recovery of module performance in intense agriculture areas is of 0.5 mm [13]. However, during long periods without rain, like summer, dust accumulation decreases panels' performance [27].

Different tools are used to characterize the elements that affect the performance of photovoltaic panels. 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 [14]. The applicability of SEM / EDS for the characterization of different dust samples has been demonstrated in recent studies which have analyzed environmental dust [28], the presence of antimony and bromine in high impact polystyrene polymers [15], the water content in powder derived from cement kilns [16], the composition of demolished materials and the risks they represent to health [29], among others.

In Peru, the climate of the region of Arequipa is varied, due to the different geographical areas that compose its territory: the region has a temperate dry climate (mountains) and a temperate cloudy climate (coast). Heavy precipitations increase in the months from November to March, which reduce the amount of dust particles that accumulate in photovoltaic panels, as opposed to light rain, which affect the performance by favoring the adhesion of dust particles to the panel. In Arequipa, three sources that generate dust particles that can accumulate in panels as a form of dirt have been identified. Among these we have cement, ashlar (volcanic stone) and clay (from brick production).

The objective of the present research study is to evaluate the efficiency of photovoltaic panels in the city of Arequipa, the influence of wind, rain and the accumulation of dust particles of cement, ashlar and clay, as well as the analysis of the chemical composition of the dust through 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.

Table 1. Photovoltaic panels technical specifications.

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/m2, AM1.5, 25 °C)

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.

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 meter 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 0.1mm diameter K-type thermocouples. Uncertainties were calculated using the Kline McClintock method [17] (Table 2).

Table 2. Studied uncertainties.

Parameter	Unit	Uncertainty (%)	Reference
Solar irradiance	W/m^2	± 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	$\left[\left(\frac{\delta A}{A}\right)^2+\left(\frac{\delta I_s}{I_s}\right)^2\right]^{0.5}$
PV Electric power	W	± 0.5	$\left[\left(\frac{\delta I_{PV}}{I_{PV}}\right)^2+\left(\frac{\delta V_{PV}}{V_{PV}}\right)^2\right]^{0.5}$
PV Electric efficiency	W/W	± 0.8	$\left[\left(\frac{\delta P_{pv}}{P_{pv}}\right)^2+\left(\frac{\delta P_s}{P_s}\right)^2\right]^{0.5}$

The photovoltaic panels were exposed to solar radiation (Fig. 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 characterized by its density (g/m2) and its particle size [9]. 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 generalize a type of dirt for all cases [18]. 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 [31].

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 [19], cement is the main element used in urban buildings and is present in the air in different concentrations [9], 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 [20]. 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 [21]. According to the literature, the size of particles in the atmosphere varies between 1 μm and 100 μm.

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 Dispersion Spectroscopy Detector (EDS) was used to perform an image characterization 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) [8,9]. In accordance with what was reviewed, 5 g/m2, 15 g/m2, 25 g/m2 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 (Fig. 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 W, 58 W, 73 W). To homogenize the wind speed and to distribute it evenly on the panel, a cover was placed around the fan (Fig. 3). The wind speed generated by each fan power level was measured using an anemometer. The wind speeds were 3.6 m/s, 3.9 m/s 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 characterization and morphology and chemical composition determination. The results obtained for each of the powders (clay, ashlar and cement) are shown in Figures 5, 6 and 7, respectively.

Figures 5, 6 and 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 aluminum predominated, for cement, carbon, oxygen, silicon, calcium and aluminum concentrations were the most important, and for the ashlar, carbon, oxygen, silicon, aluminum and sodium were more present. The results coincide with percentages determined in previous studies [22-24].

After performing several efficiency tests for the types of powder under study, the established dust deposition (surface density) of 5 g/m2, 15 g/m2, 25 g/m2 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 [25]. 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 Fig. 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 rain phenomenon reduces the solar radiation that attains the panels, solar radiation is not reduced to zero, since there is still visibility.

In Fig. 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 stabilize at ambient temperature. Under these conditions, there was no electricity production.

In Fig. 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 panels 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.

Declarations

Availability of data and materials

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

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

Stamber Alvaro Ramírez-Revilla carried out sample preparation, methodology, supervision, and editing. Juan José Milón Gúzman conducted visualization and data curation. Karim Cipriano Navarrete 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.

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References

1. W. Charfi, M. Chaabane, H. Mhiri y P. Bournot, «Perfomance evaluation of a solar photovoltaic system» Energy Reports, vol. 4, pp. 400 - 406, 2018.
2. M. Mussard y M. Amara, «Perfoamnce of solar photovoltaic modules under arid climatic conditions: A review» Solar Energy, vol. 174, nº 1, pp. 409-421, 2018.
3. A. Hussain, A. Batra y R. Pachauri, «An experimental study on effect of dust on power loss in solar photovoltaic module» Renewables: Wind, Water, and Solar, vol. 4, nº 9, pp. 1-13, 2017.
4. Y. Kumar SIngh, S. Dubey, K. Pandey y O. S. Sastry, «Perfomance of HIT module in different climatic condition in India» Materials Today: Proceedings, vol. 17, nº 1, pp. 321-328, 2019.
5. A. Maftah y M. Maaroufi, «Experimental evaluation of temperature effect of two different PV Systems Performances under arid climate» Energy Procedia, vol. 157, pp. 701-708, 2019.
6. A. Syafiq, A. Pandey, N. Adzman y N. A. Rahim, «Advances in approaches and methods for self-cleaning of solar photovoltaic panels» Solar Energy, vol. 162, pp. 597-619, 2018.
7. U. Mehmood, F. A. Al-Sulaiman y B. S. Yilbas, «Characterization of dust collected from PV modules in the area of Dhahran, Kingdom of Saudi Arabia, and its impact on protective transparent covers for photovoltaic applications» Solar Energy, vol. 141, p. 203–209, 2017.
8. M. S. El-Shobokshy y F. M. Hussein, «Effect of dust with different physical properties on the performance of photovoltaic cell» Solar Energy, vol. 51, nº 6, pp. 505-511, 1993.
9. A. M. Arroyo Fernández, Caracterización e influencia de la suciedad en instalaciones fotovoltaicas., Sevilla: Universidad de Sevilla, 2010, pp. 136 -165.
10. G. A. Mastekbayeva y S. Kumar, «Effect of dust on the transmittance of low density polyethylene glazing in a tropical climate» Solar Energy, vol. 68, nº 2, pp. 135-141, 2000.
11. H. Goverde, D. Goossens, J. Govaerts, V. Dubey, F. Catthoor, K. Baert, J. Poortmans y J. Driesen, «Spatial and temporal analysis of wind effects on PV module temperature and performance» Sustainable Energy Technologies and Assessments, vol. 11, pp. 36-41, 2015.
12. A. López, V. E. Parnás y J. Cataldo, «Experimentos en túnel de viento sobre paneles fotovoltaicos montados en el suelo,» Revista ingeniería de construcción, vol. 34, nº 1, pp. 15-24, 2019.
13. J. R. Caron y B. Littmann, «Direct monitoring of energy lost due to soiling on first solar modules in California» 2012 IEEE 38th Photovoltaic Specialists Conference (PVSC) PART 2, Austin, TX, pp. 1-5,

2012.
14. J. Wagner, S. Chosal, T. Whitehead y C. Metayer, «Morphology, spatial distribution, and concentration of flame retardants in consumer products and environmental dusts using scanning electron microscopy and Raman micro-spectroscopy» Environment International, vol. 59, pp. 16-26, 2013.
15. R. D. Holbrook, J. M. Davis, K. C. Scott y C. Szakal, «Detection and speciation of brominated flame retardants in high-impact polystyrene (HIPS) polymers» Journal of Microscopy, vol. 246, nº 2, pp. 143-152, 2012.
16. P. Czapik, J. Zapta-Staweta, Z. Owsiak y P. Stepien, «Hydration of cement by-pass dust» Construction and Building Materials, vol. 231, pp. 1-9, 2020.
17. R. J. Moffat, «Describing the uncertainties in experimental results» Experimental Thermal and Fluid Science, vol. 1, nº 1, pp. 3-17, 1988.
18. J. K. Kaldellis y M. Kapsali, «Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements» Energy, vol. 36, nº 8, pp. 5154-5161, 2011.
19. D. C. Alavarez-Rozo, J. Sánchez-Molina, F. A. Corpas-Iglesias y J. F. Gelves, «Características de las materias primas usadas porlas empresas del sector cerámico del áreametropolitana de Cúcuta (Colombia),» Boletín de la Sociedad Española de Cerámica y Vidrio, vol. 57, nº 6, pp. 247-256, 2018.
20. Ó. Ruis Bueno, J. M. Gonzales Zarate, V. Bernedo Málaga, E. A. Prado y A. Prado Espinoza, Salud ocupacional en las canteras de sillar, distritos de Yura y Cerro Colorado, Arequipa – 2014, Arequipa: Universidad Ciencias de la Salud, 2014.
21. M. Abderrezek y M. Fathi, «Experimental study of the dust effect on photovoltaic panels' energy yield» Solar Energy, vol. 142, pp. 308-320, 2017.
22. J. Shao, J. Gao, Y. Zhao y X. Chen, «Study on the pozzolanic reaction of clay brick powder in blended cement pastes» Construction and Building Materials, vol. 213, pp. 209-215, 2019.
23. A. A. Aliabdo, A.-E. M. Abd-Elmoaty y H. H. Hassan, «Utilization of crushed clay brick in cellular concrete production» Alexandria Engineering Journal, vol. 53, nº 1, pp. 119-130, 2014.
24. D. M. M. Gallegos Florez, Estudio de la actividad fotocatalítica de un recubrimiento de TiO2-TEOS sobre el Sillar por el método de spray coating en la degradación de gases NO., Arequipa -Peru: Universidad Nacional de San Agustín de Arequipa, 2019.
25. M. Ali, M. H. Iqbal, N. A. Sheikh, H. M. Ali, M. S. Manzoor, M. M. Khan y K. F. Tamrin, «Performance Investigation of Air Velocity Effects on PV Modules under Controlled Conditions» International Journal of Photoenergy, pp. 1-10, 2017.
26. D. Goossens, H. Goverde y F. Catthoor, «Effect of wind on temperature patterns, electrical characteristics, and performance of building-integrated and building-applied inclined photovoltaic modules» Solar Energy, vol. 170, pp. 64-75, 2018.
27. J. Zorrilla-Casanova, M. Piliougine, J. Carretero, P. Bernaola, P. Carpena, L. Mora-López y M. Sidrach-de-Cardona, «Analysis of dust losses in photovoltaic modules» World Renewable Energy Congress 2011 - Sweden. Photovoltaic Technology (PV), nº 057, pp. 2985-2992, 2011.

28. T. F. Webster, S. Harrad, J. R. Millette, R. D. Holbrook, J. M. Davis, H. M. Stapleton, J. G. Allen, M. D. McClean, C. Ibarra, M. A.-E. Abdallah y A. Covaci, «Identifying transfer mechanisms and sources of decabromodiphenyl ether (BDE 209) in indoor environments using environmental forensic microscopy» Environmental Science and Technology, vol. 43, nº 9, pp. 3067-3072, 2009.
29. C. Oliveira, C. Reis, J. C. Abrantes, L. T. Silva, P. L. Silva y J. F. Silva, «Study of the dust produced in rehabilitation works» Procedia Structural Integrity, vol. 22, pp. 144-150, 2019.
30. D. Goossens y E. Van Kerschaever, «Aeolian dust deposition on photovoltaic solar cells: the effects of wind velocity and airborne dust concentration on cell performance» Solar Energy, vol. 66, nº 4, pp. 277-289, 1999.
31. R. Conceição, H. G. Silva, J. Mirão, M. Gostein, L. Narvarte y M. Collares-Pereira, «Saharan dust transport to Europe and its impact on photovoltaic performance: A case study of soiling in Portugal» Solar Energy, vol. 160, pp. 94-102, 2018.

Figures

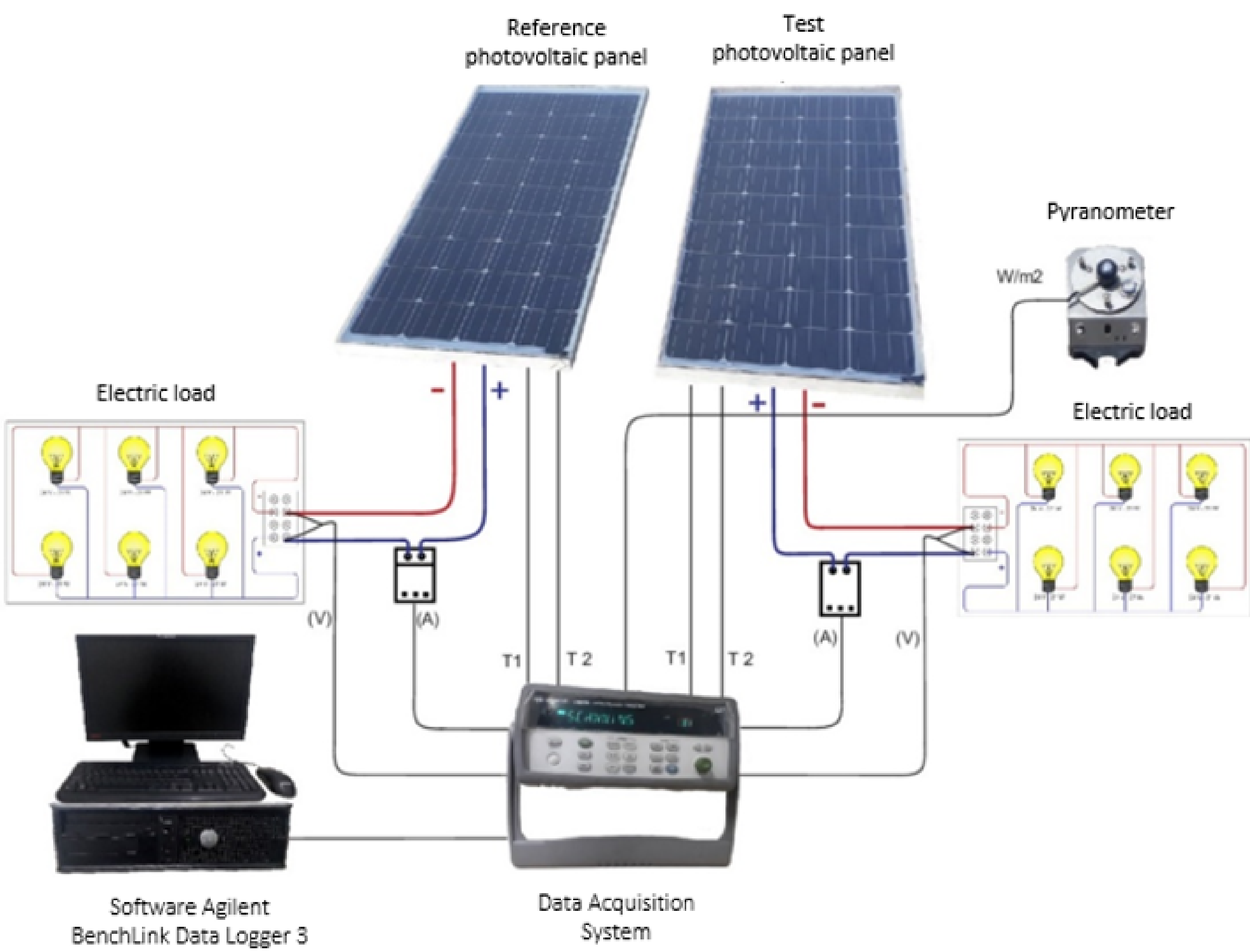


Figure 1

Photovoltaic system installation scheme.

Figure 2

Dust sample deposited on the photovoltaic panel.

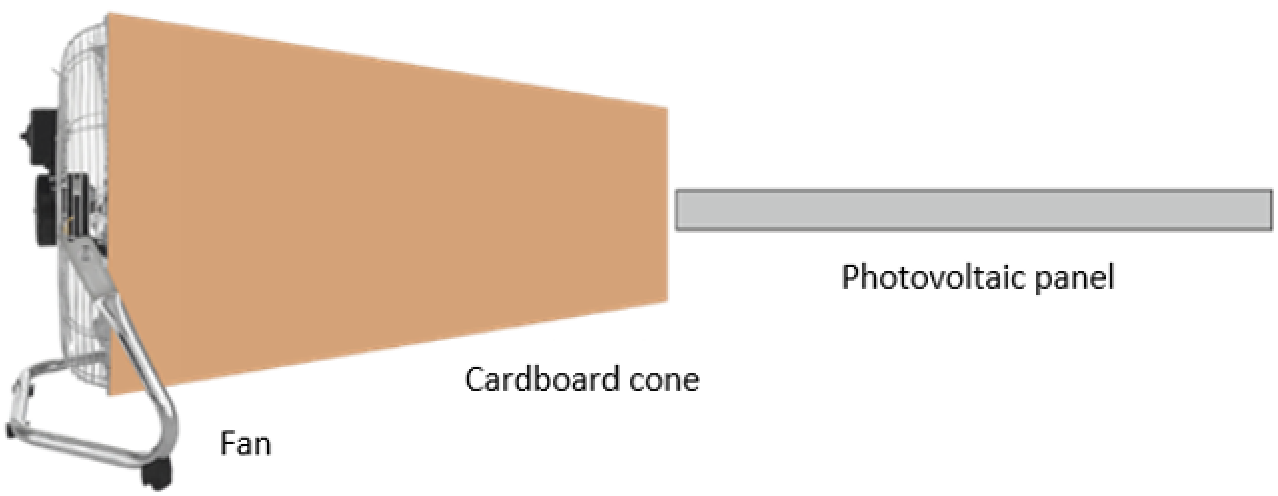


Figure 3

Diffuser design.

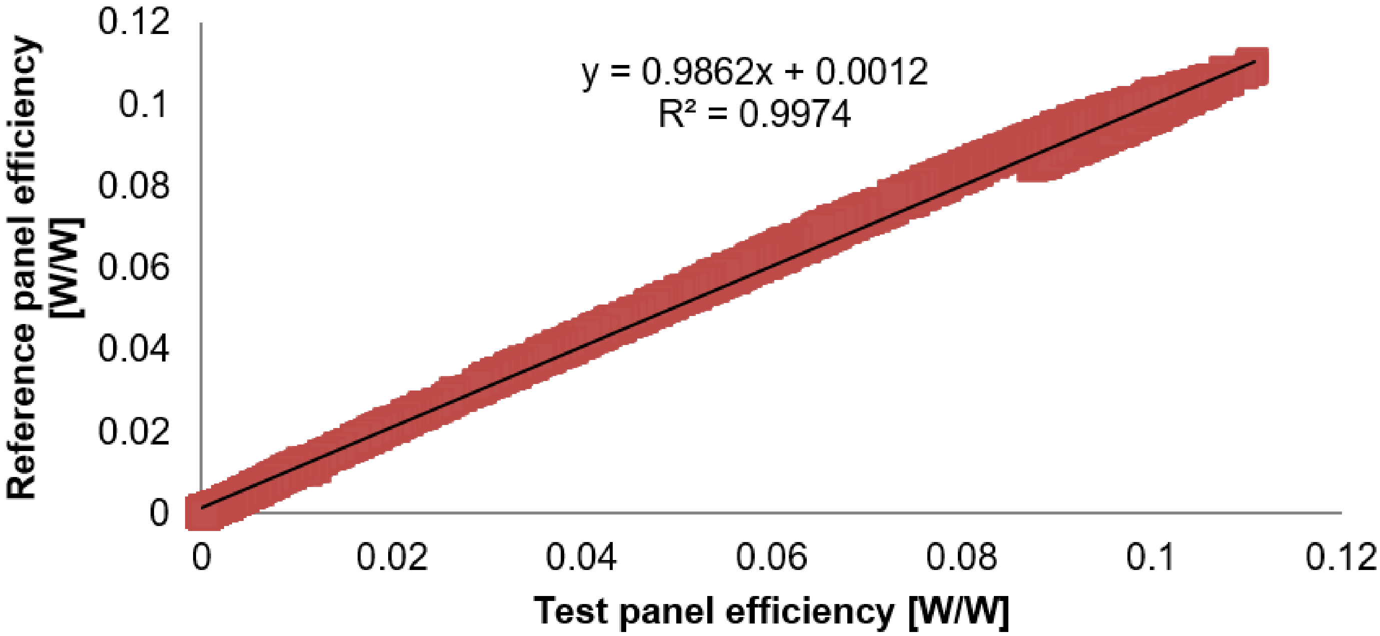


Figure 4

Comparison of Pr and Pp efficiencies (both panels were clean).

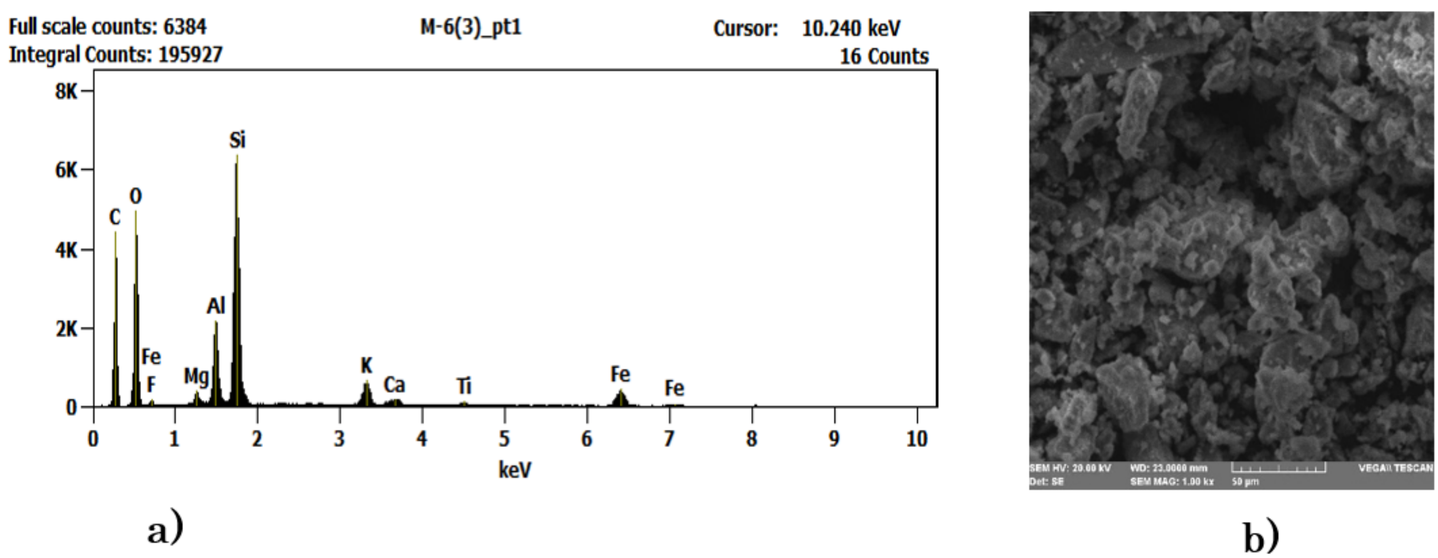
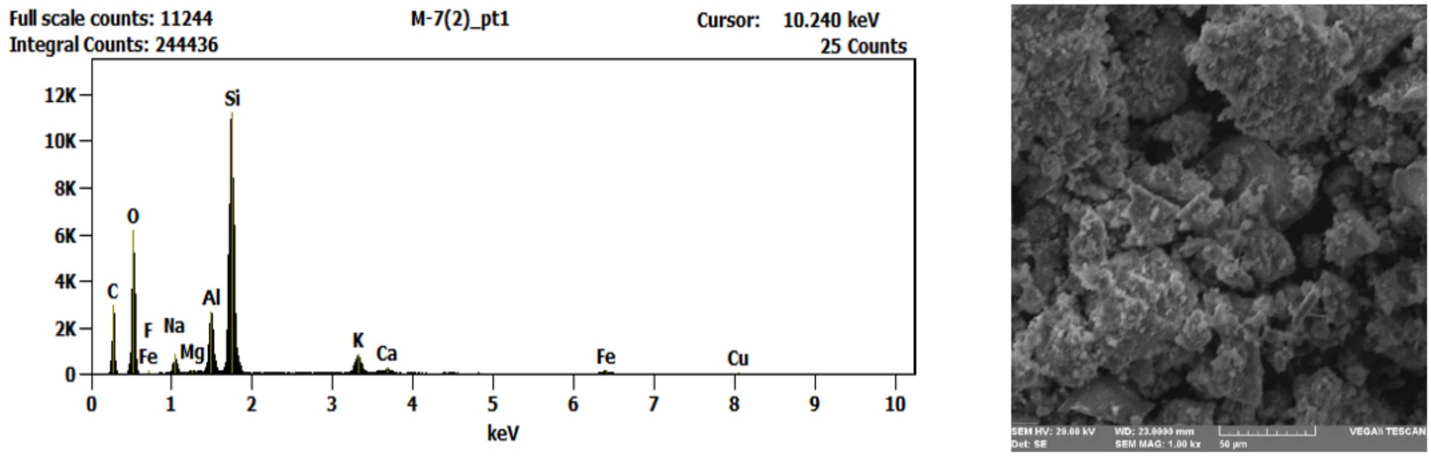


Figure 5

SEM/EDS results for clay dust (<75 μm). a) EDS spectra and b) SEM microphotography.

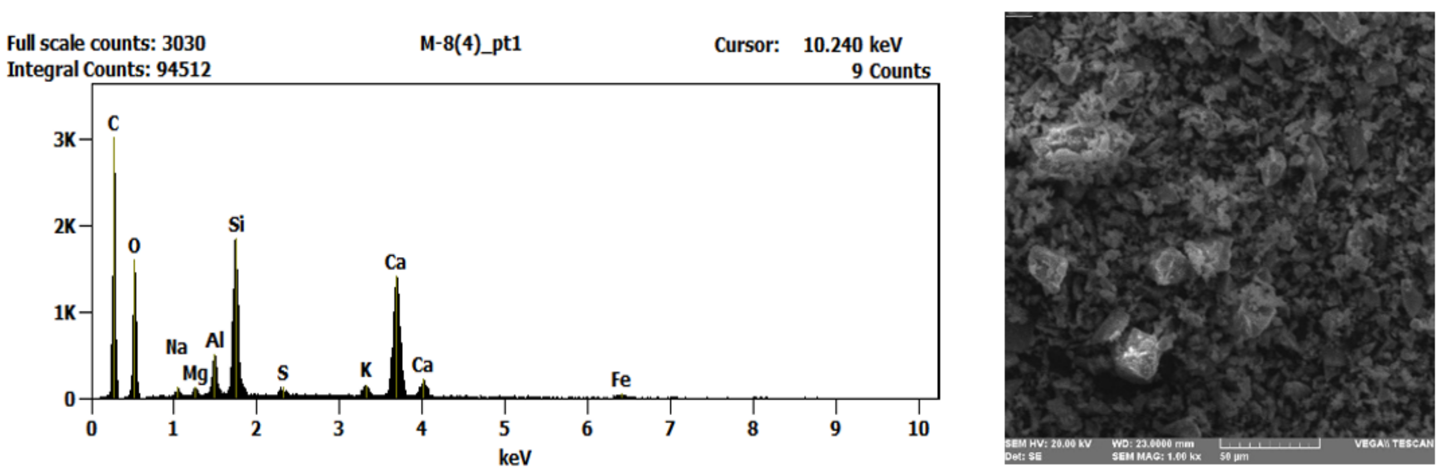


a

b

Figure 6

SEM/EDS results for ashlar dust (<75 μm). a) EDS spectra and b) SEM microphotography.



a)

b

Figure 7

SEM/EDS results for cement dust (<75 μm). a) EDS spectra and b) SEM microphotography.

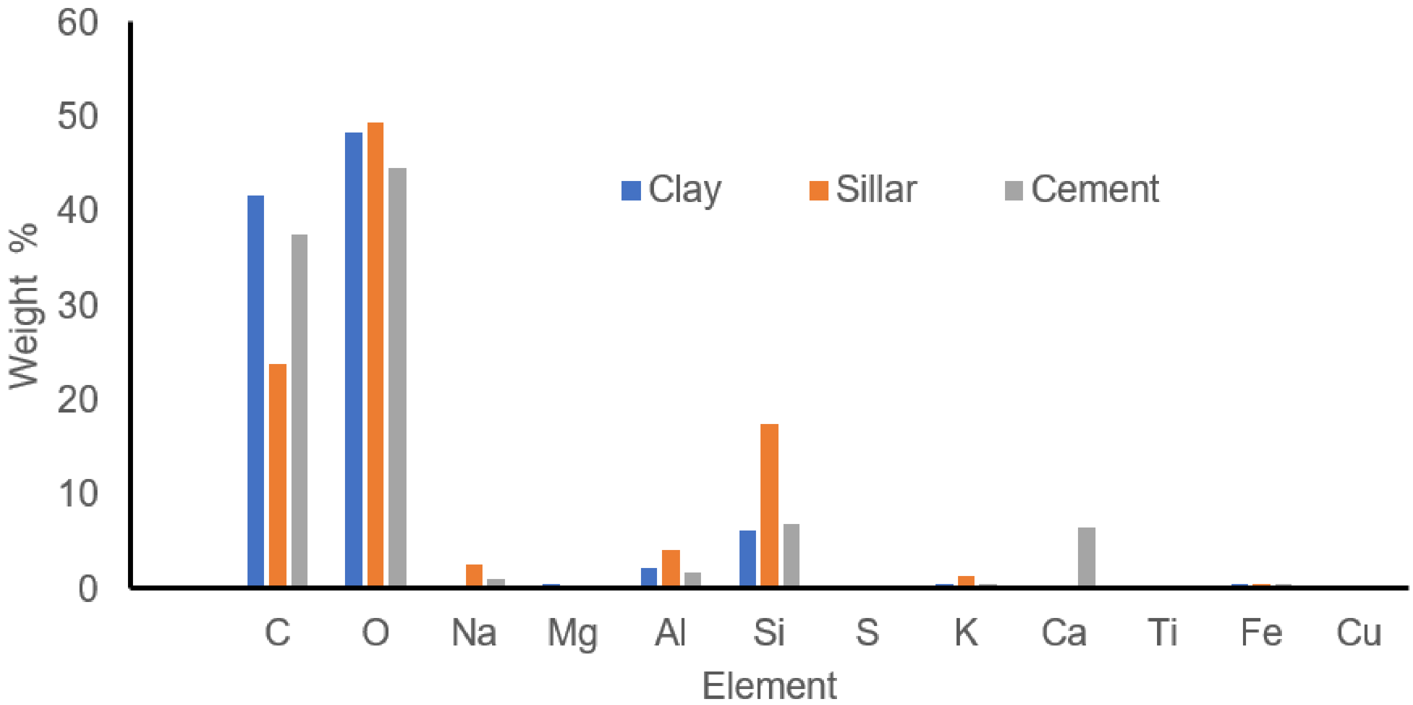


Figure 8

Chemical composition of the analyzed dusts (in percentage) (<75 μm) obtained through SEM/EDS.

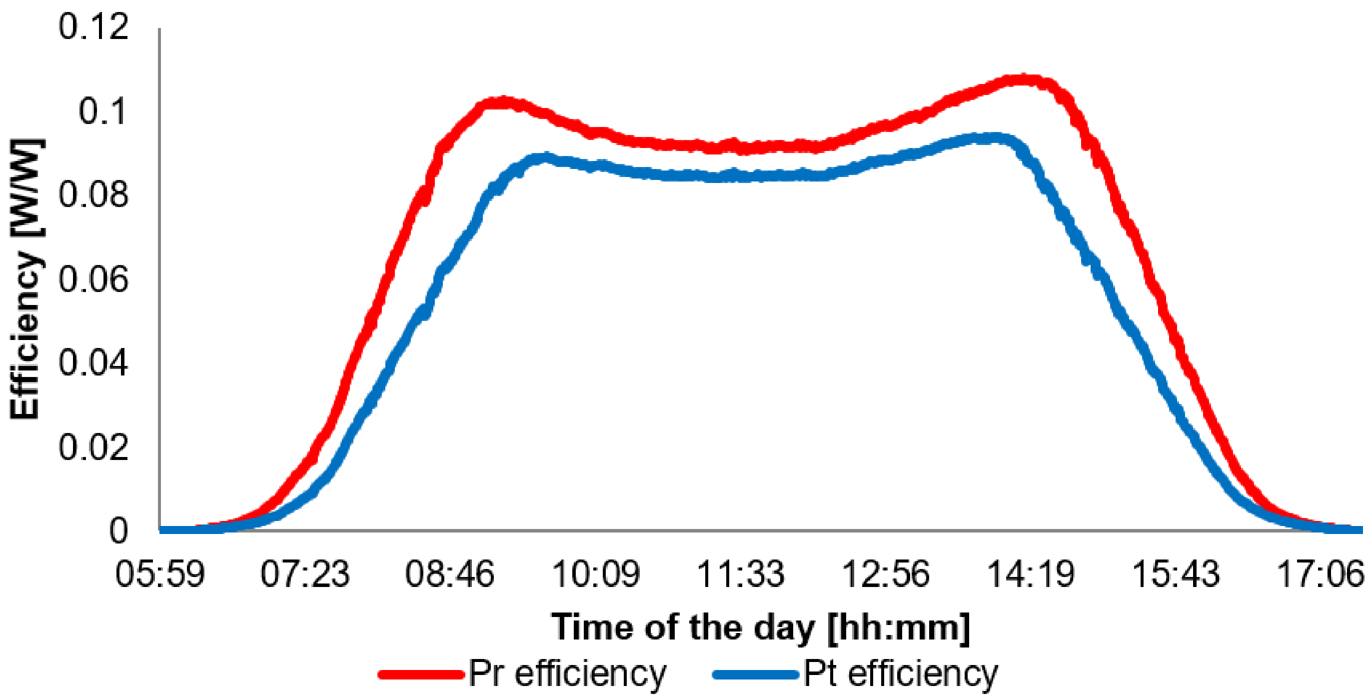


Figure 9

Pr and Pp efficiency in the presence of 5 g/m2 of ashlar dust (< 75 μm).

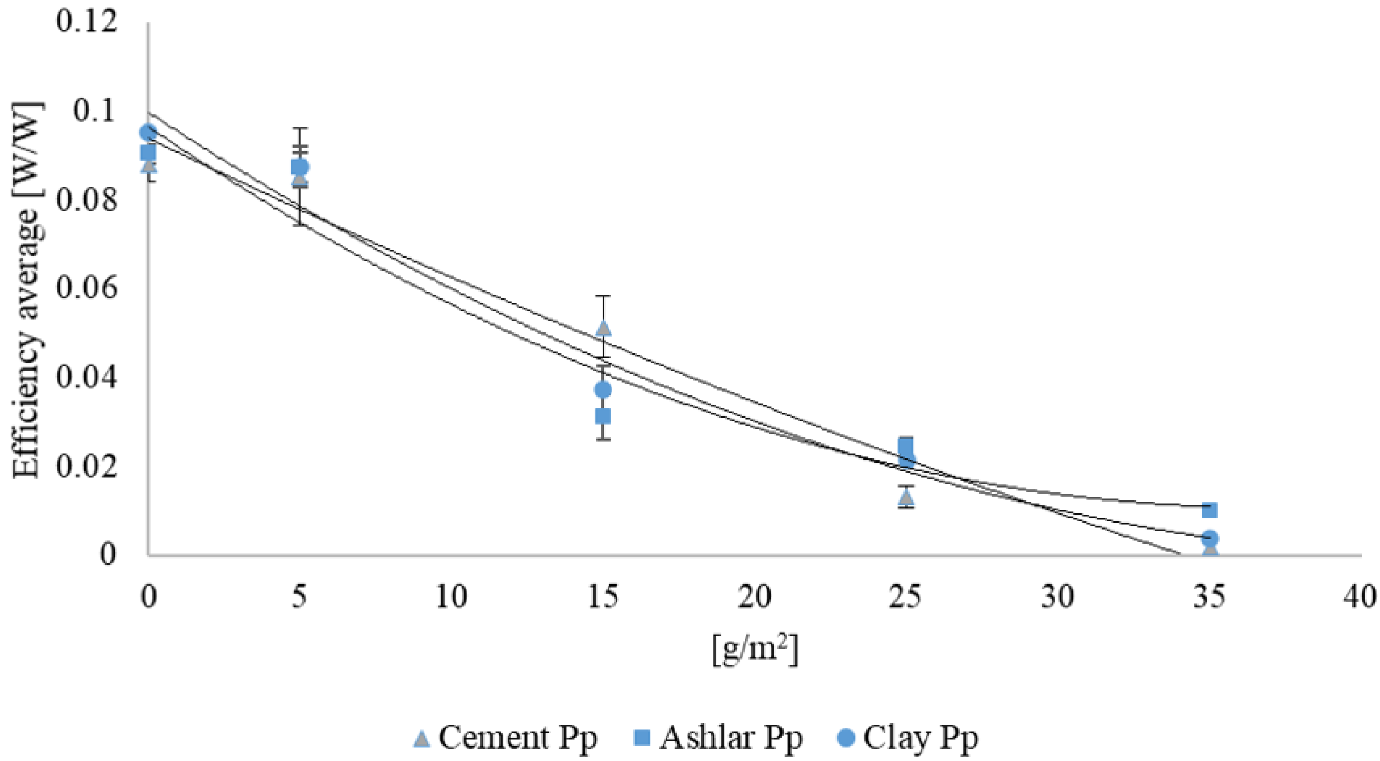


Figure 10

Average efficiency for different cement, ashlar and clay dust deposits (< 75 μm).

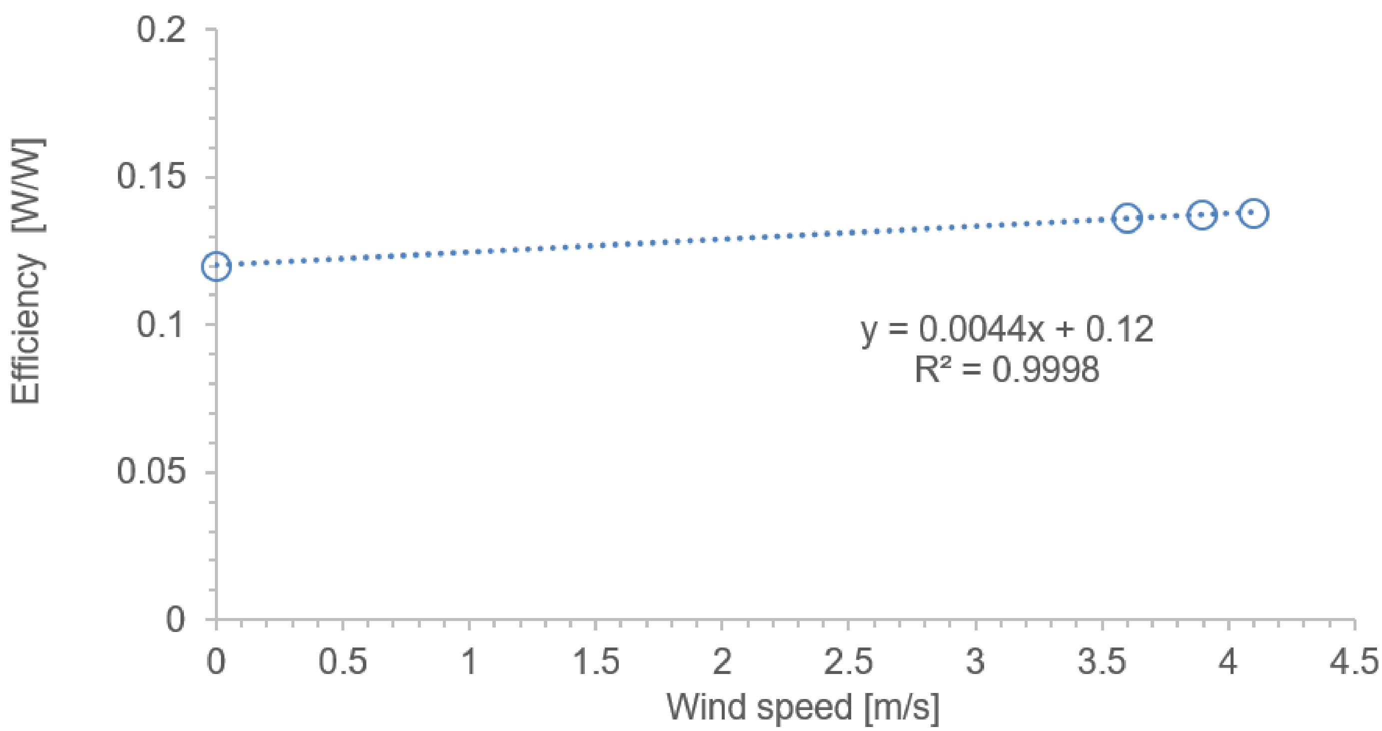


Figure 11

Photovoltaic panels average efficiency with wind influence.

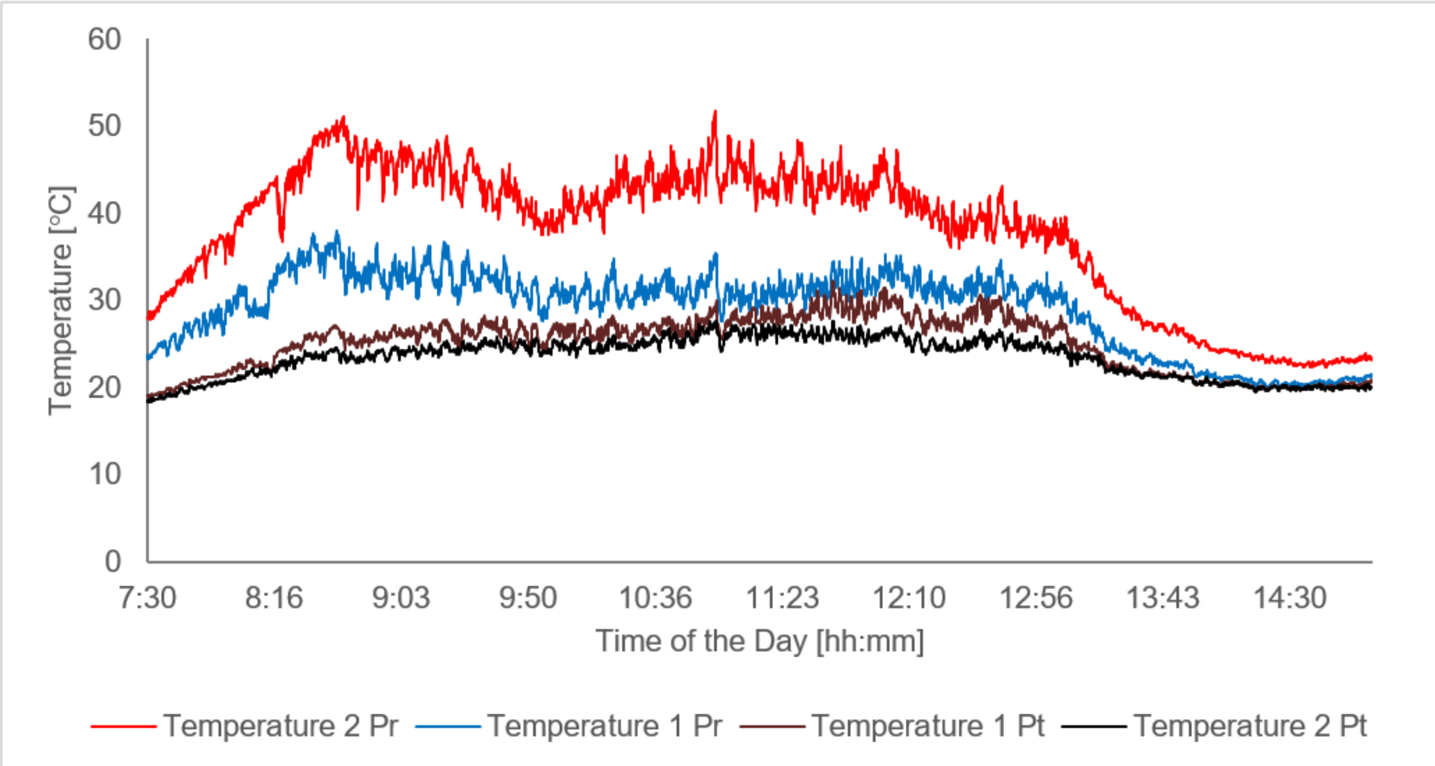


Figure 12

Temperature of the panels influenced by wind at a speed of 4.1 m/s.

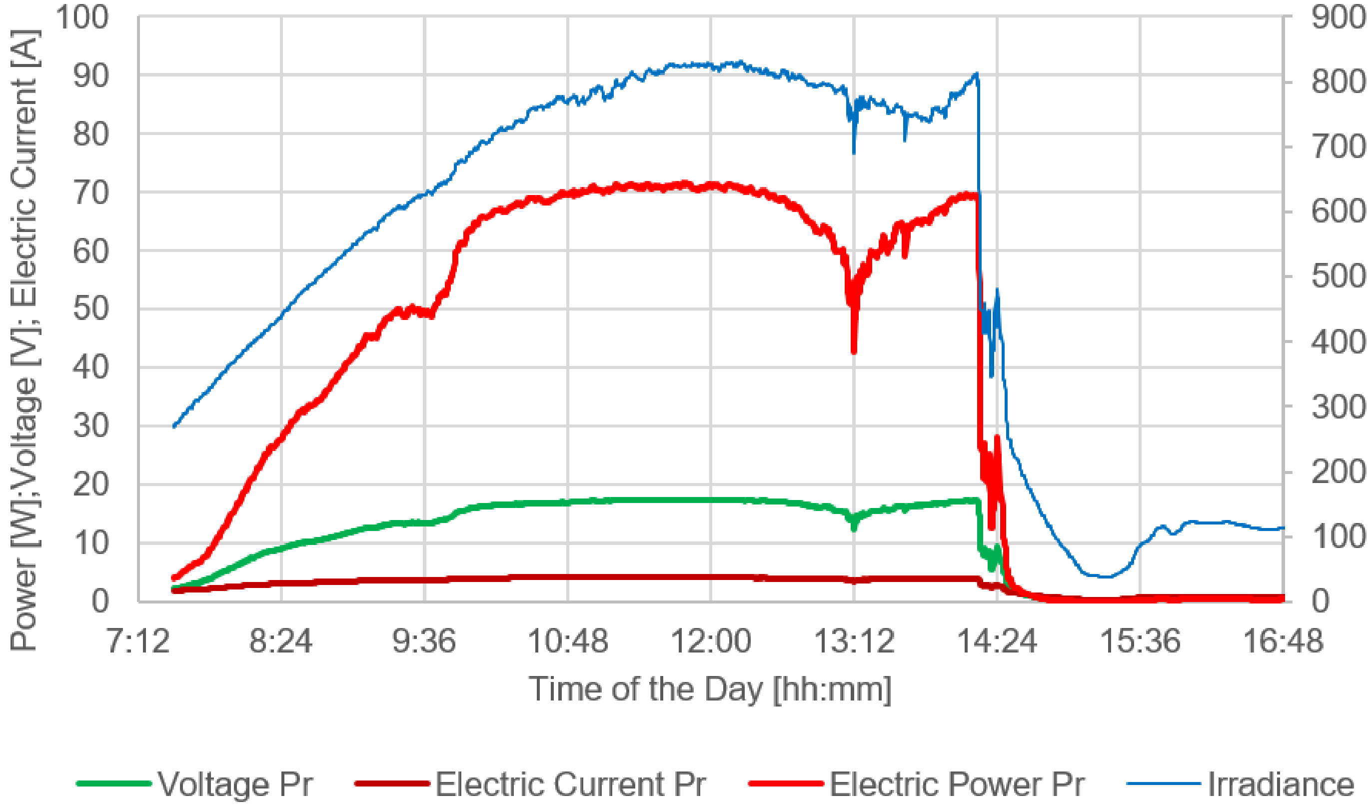


Figure 13

Rain tests, behavior of the electric parameters of the panel.

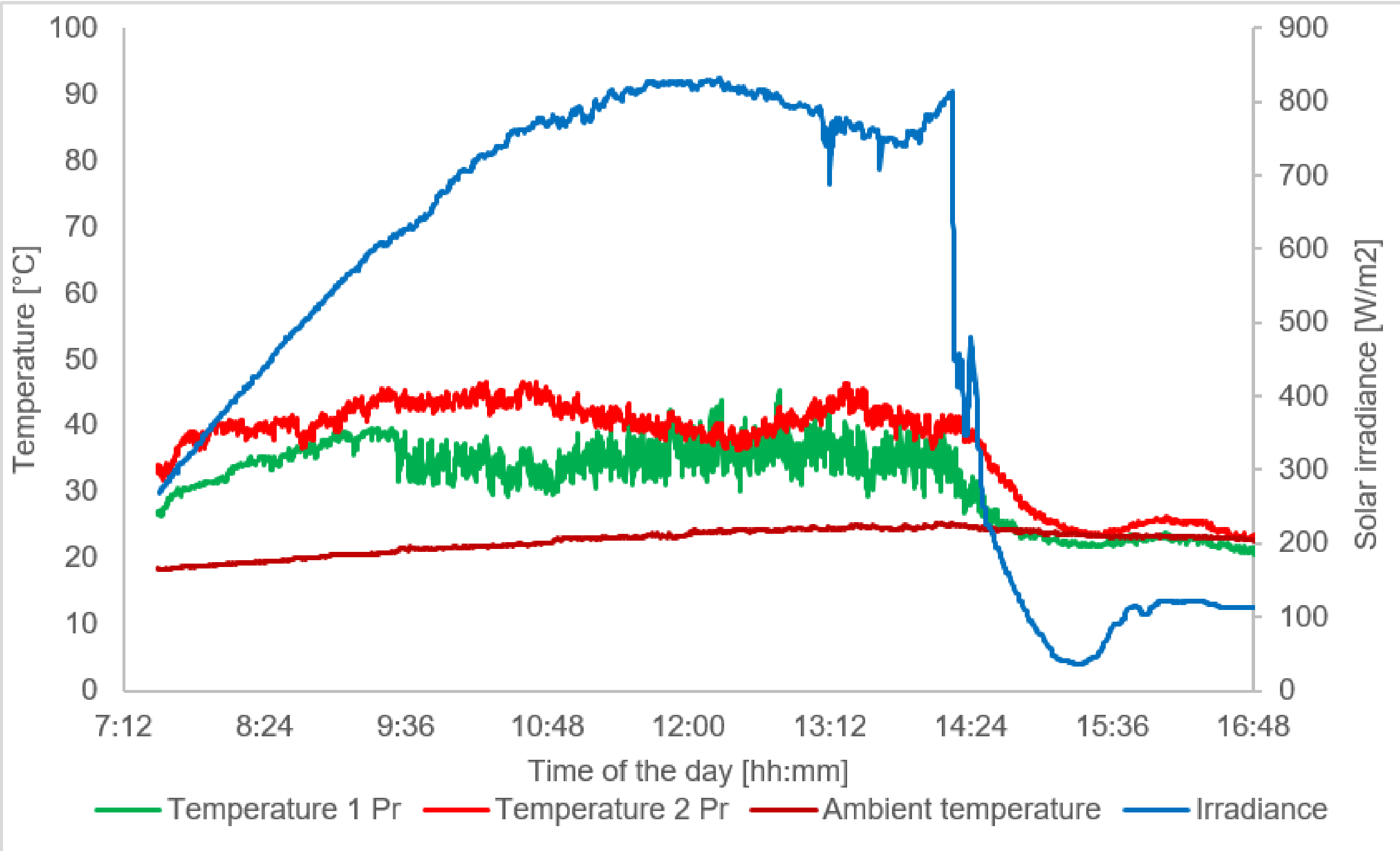


Figure 14

Rain tests, temperature variation.

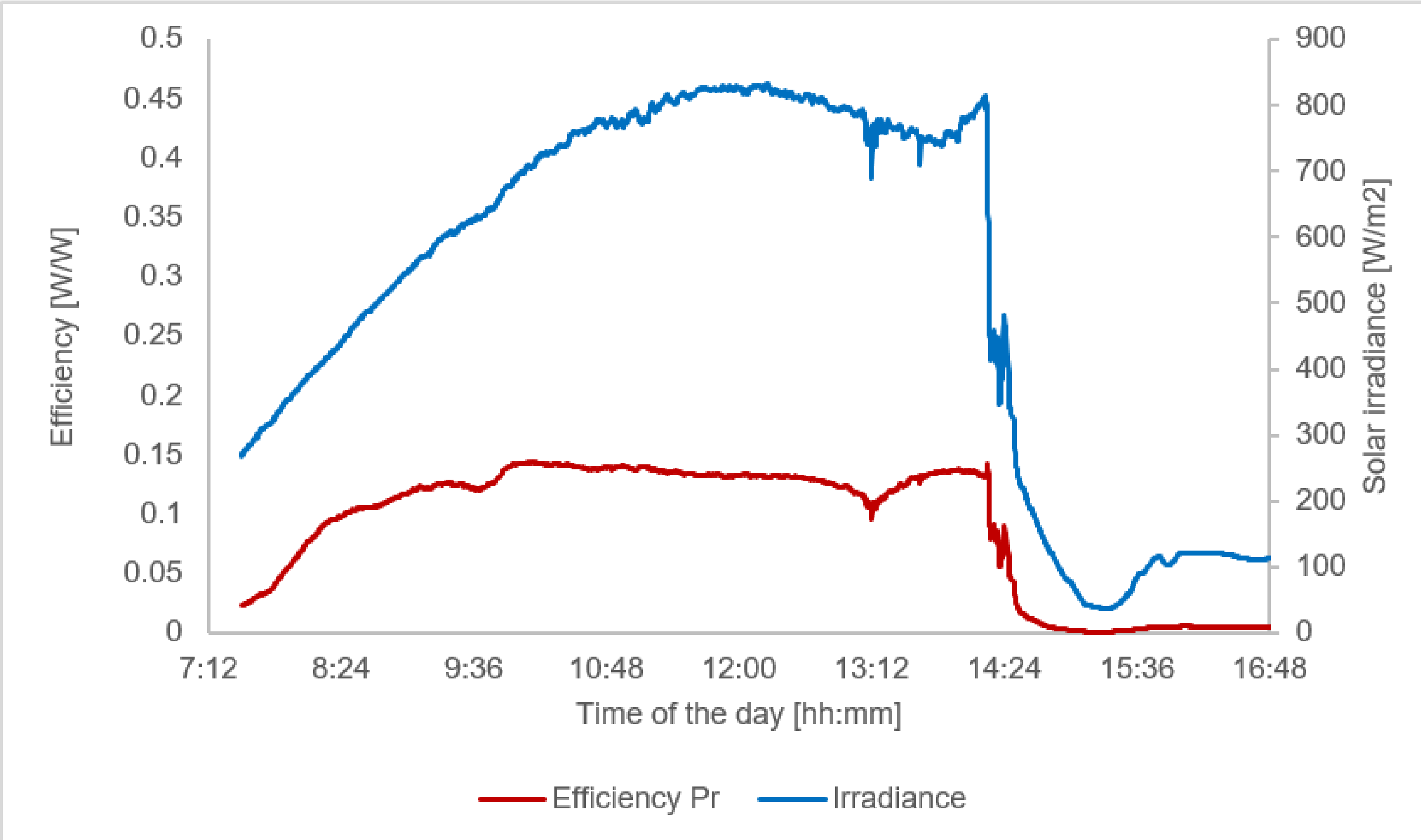


Figure 15

Rain tests, energy efficiency.