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Experimental investigation of the soiling effect on the performance of monocrystalline photovoltaic systems

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Abstract

Due to the high solar irradiation records, desert regions are the most suitable for hosting photovoltaic power plants [1]. Nevertheless, these regions are characterized by the presence of dust and aerosols that can be deposited on the surface of the panels causing a considerable drop on the plants efficiency, thus, the power production.
The objective of this study is to measure and understand the soiling's effect on the performances of a 16.56 kW_c monocrystalline grid connected PV system, after six months of exposition without cleaning at Green Energy Park research facility [2]. This facility is located in the mid-south of Morocco and characterized by a semi-arid climate. Besides, chemical analysis of the dust composition has been conducted to have an idea on the aerosols origin emission source.
Results shown, that the cumulative power drop of the soiled string after six months was around 124 kWh. The daily power drop, in average, is of 2.7kWh/day during the dry period and of 0.07kWh/day during the rainy period. This is linked to a daily soiling rate of 0.32%/day and 0.02%/day during the dry and the rainy periods respectively.
Regarding the dust chemical-analysis, the XRD results highlight the presence of silicon, alumina, calcium, iron, which are may be coming from a construction site close by. Besides, potassium, magnesium and phosphorus that may be coming from a phosphate mine in the area of our field of study.

Keywords: Photovoltaic, dust effect, soiling ratio, energy drop and performance ratio.

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1. Introduction

Nomenclature:

GEP	Green Energy Park
PV	Photovoltaic
Id	Current of the dusty string.
Ic	Current of the cleaned string.
Ed	Energy of the dusty string.
Ec	Energy of the cleaned string.
PRd	Performance ratio of the dusty string.
PRc	Performance ratio of the cleaned string.
SR	Soiling ratio
SEM	Scanning electron microscopy
IRESEN	Research Institute for Solar Energy and New Energies
STC	Standard Test Conditons
Pmax	Maximum power
Imp	Maximum power current
Vmp	Maximum power voltage

Energy is an important development factor of a country. In recent decades, energy has become a major problem worldwide as fossil fuel resources decline while global energy demand increases dramatically [1].

Renewable energies are a good way to promote sustainable development, especially for countries that have significant potential in terms of renewable energy resources such as sun, wind, etc. Among these countries, Morocco is particularly well placed to use this potential. Aware of the promising future of green energy sources, Morocco has prioritized the development of renewable energies throughout its territory to increase their share to 42% of total capacity by 2020 [2-4].

For power generation, photovoltaic (PV) and concentrated solar thermal (CSP) systems are the most used technologies to convert solar energy. Considerable time and money has been invested to improve the performance of the solar system and to ensure reasonable reliability by focusing on material development and system design. Besides these parameters, the variation of weather conditions from one place to another has a corresponding effect on the performance of the PV modules in different regions [16]. Parameters that can affect PV module performance include solar radiation, wind speed, precipitation, temperature, humidity, and the dust deposition.

Accumulation of dust, bird droppings, and other components on the surface of PV modules can cause losses of the energy yield, especially in desert areas. However, the desert regions are the most suitable for photovoltaic electricity production tanks to the abundant availability of solar radiation throughout the year.

It is only recently that the problem of soiling has been at the forefront because of the increased interest in solar energy in countries where such a phenomenon is a real problem.

Moisture is a factor whose effect on soiling has been studied in several studies [12-14]. As relative humidity increases, aerosols become heavier by absorbing water vapor and their rate of fall on photovoltaic modules and mirrors increase due to the increase in gravitational force. Once the dust is deposited on the surface of the systems, the droplets of water from the moisture form a bonding force between them and the surface. In addition, when the weather becomes dry, the cementing process can take place resulting in greater adhesion of these particles to the surface.

Wind is a natural factor that ensures the emission and transport of dust particles at different heights and speeds according to their properties. Wind speed is considered one of the meteorological parameters that most affects the soiling of PV panels and solar mirrors.

The evaluation of the effect of wind speed on the rate of soiling of the surfaces of solar components has been the subject of several studies [15, 17 and 18]. Pennetta [17] found a correlation between dust density and wind speed, which confirms the crucial role of strong winds in the generation and air transport of dust.

Results of some experimental studies that reveal the impact of soiling on the performance of solar systems are as follows: For instance, the one conducted by Kaldellis et al.[5], They studied accumulation of dust on photovoltaic panels and they found that the efficiency of the PV module decreased to 0.4% as the dust density increased by 0.09 mg/cm². Similarly, Rajput and Sudhakar [6] found that the power and efficiency of soiled modules decreased by up to 92% and 89% respectively compared to clean modules. Adinoyi and Said [7] studied the effect of dust on performance in Saudi Arabia. After the six-month exposure to the natural environment, a 50% reduction in the power of the modules was covered. Similarly, Mohamed and Hasan [8] marked a 50% decrease in the PV efficiency of 4 polycrystalline panels due to dust accumulation. Zorrilla-Casanova et al. [9] found that the average daily energy losses caused by dust; deposited on the surface of the photovoltaic module; is about 4.4%. However, in long periods without rain, the daily energy losses reach 20% and above. Sulaiman et al. [10] found that dust accumulated on the surface of a photovoltaic solar panel can reduce its efficiency by up to 50%. Dorobantu.l [11] found that pollution and dust caused by road traffic or agricultural activities accumulate rapidly and can reduce the efficiency of photovoltaic cells by 20% during a dry summer, and a very thin layer of dust may reduce the conversion of solar energy by 40%.

Generally, soiling is a complex problem; it depends a lot on the location and climatic conditions of the installation site, the deep understanding of this phenomenon is essential in order to choose the suitable location for the installation sites accordingly, the best choice to optimize the cleaning strategies and its adaptation to dusty areas as well.

This work is divided into two parts; the first is a local dust analysis to define the chemical composition of our dust sample using X-ray fluorescence and energy dispersive spectroscopy analysis.

The second part is an experimental study whose objective was the evaluation of the soiling impact on the photovoltaic performance by calculating the soiling ratio, the energy difference and the performance ratio difference of a Monocrystalline PV system, installed at Green Energy park research facility located at Benguerir (mid-South of Morocco) and also to calculate the cleaning cost during the dry and rainy period.

Results shown, that the cumulative power drop of the soiled string after six months is around 124 kWh. The daily power drop, in average, is 2.7 kWh/day during the dry period and of 0.07 kWh/day during the rainy period. his is equivalent to a daily soiling ratio of 0.32%/day and 0.02%/day during the dry and the rainy periods respectively. The dust analysis shows that oxygen makes up the bulk of the dust composition, followed by silicon, alumina, calcium and potassium, as well as the presence of magnesium, phosphorus and other elements.

2. Dust composition and chemical analysis:

The nature of the deposits is of great importance in determining the rate of soiling observed on the surface of the materials [19, 20]. In the work of Kazem for example [20], the effect of three different types of soiling on the rate of soiling of PV panels, namely, red soil, ashes and sand, has been evaluated. The results obtained show that the samples contaminated with ash have the most performance losses compared with the other samples with a loss of 26.5% compared to 7.5% for the red soil and 5% for the soiling by the sand particles.

In the same context, research carried out by Khatib in the literature [21] analyzed the effect of several other types of soiling on the performance ratio of PV panels. These soil particles are red soils, ashes, sand, calcium carbonate and silica. They found that the voltage and the PV power decreased regardless of the type of soiling particles. However, they found that ashes are the soiling particles that represent the most performance losses of the samples compared to other types of pollutants.

It can be seen from these literature overview that the nature of the dust particles significantly affects the output voltage, the performance of the system, hence the need to deepen understanding on the nature of the dust particles in terms of composition, shape and size.

2.1. X-ray fluorescence analysis:

In order to identify the composition of our dust sample, dust was collected from the surface of the panels installed at GEP in from two different periods (2015 and 2017) as shown in the Fig.1. these samples were analysed using X-ray fluorescence.

The X-ray fluorescence analysis is a very successful method for dust characterization thanks to its speed and simplicity of implementation. This non-destructive method, which exploits the fluorescence of elements in the X-ray domain, provides quantitative information on the composition of the sample. This technique is considered reliable for samples with good homogeneity. In the opposite case, several analyze are necessary for the same sample.

The results of this characterization technique of our sample are indicated in Fig.2 which gives respectively the percentage chemical elements mineralogical analysis of the sample.

From our results, the main chemical constituents were silicon (Si) derived from desert sand (quartz or silicon dioxide, SiO2) and calcium (Ca) from mineral calcite (calcium carbonate, CaCO3); and other minor constituents consisted of aluminum, iron, magnesium, potassium and sodium.

Fig. 1. The dust collects

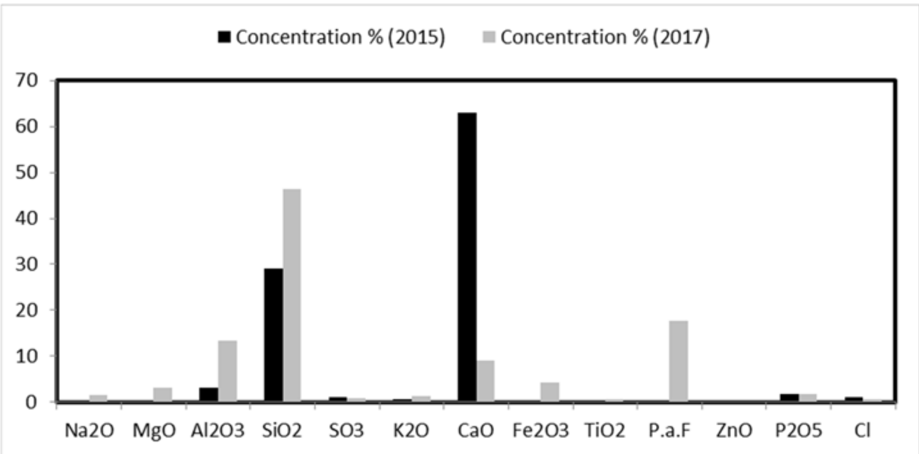

Fig. 2. The results of the fluorescence analysis of the local soil

2.2. Microscopically analysis:

Dust analysis by scanning electron microscopy (SEM) showing the morphology of the dust sample is given in Fig.3. The micrograph shows that the dust has different and irregular particle sizes. This distribution of particle sizes and shapes influences the shading effect of dust on the surface of the PV module; thus, the power output. The higher the density of the dust, the lower is the quantity of solar radiation transmitted by the glass cover of the module to the solar cells.

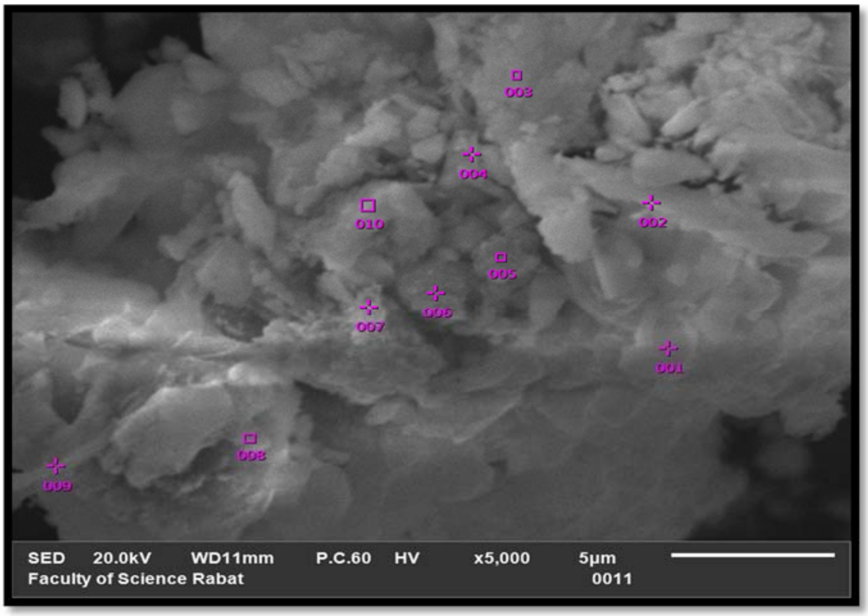

Fig. 3. SEM micrograph of the dust sample.

The analysis of the dust was done on ten zones thanks to the SEM; the results are displayed in table 6, which shows that there are major components present in all the zones like: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), potassium (K), magnesium (Mg), calcium (Ca), and phosphorus (P). Nevertheless, some components were detected in only some areas, like titanium (T), which was detected in areas (1,4 and 8), sulfur (S) in (5,6,7 and 10), sodium (Na) in zones (8 and 9), zinc in (6,8 and 9) and finally chlorine in (5,6,7,8,10). Fig.4 represents the percentage of each atom in the different zones, in which it was found that oxygen and the major component with a large percentage present in all zones, followed by silicon and aluminum which are omnipresent by a minus percentage. 25%, all remaining components are at 5% per zone.

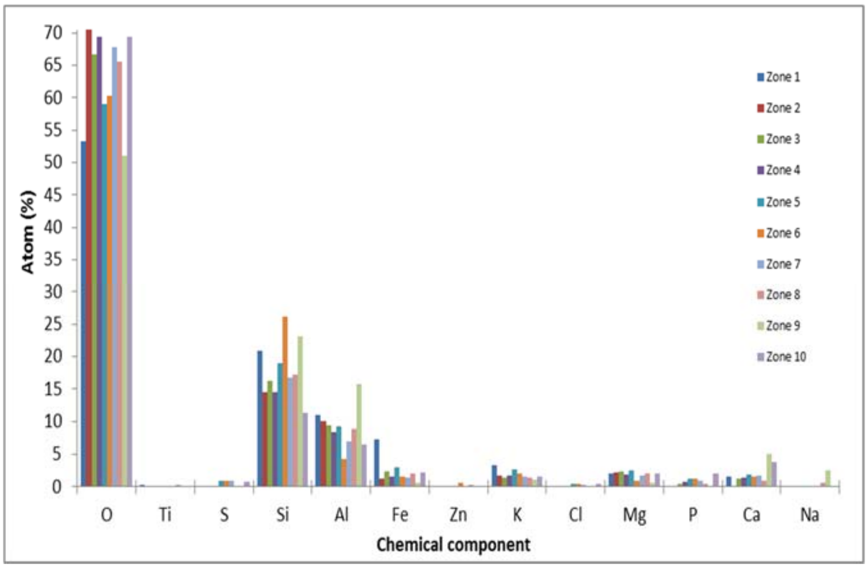

Fig. 4. Elemental composition of the dust sample.

3. Site exposition's description and methodology:

As mentioned above, a total capacity of 100 kWp form different PV technologies, such as, monocrystalline (m-Si), polycrystalline silicon (P-Si), amorphous (a-Si), cadmium telluride (CdTe), copper-indium-gallium-selenium (CiGS) and high concentration photovoltaic (HCPV) were installed at the Solar Test Facility, Green energy Park, Benguerir Fig.5 (Latitude 32.22N, Longitude -7.94E, altitude 449 m) with a tilt angle of 31° and facing south. This site has a semi-arid climate with a daily global horizontal irradiation (GHI) records between 1.2 and 8.89 kWh/m²/day, a humidity range of 12-93.95 % and an average ambient temperature of 24 °C.

The investigated PV system in this study is a new silicon PV conception without EVA encapsulation Fig.6. The system's nominal capacity is 16.5 kW_p and is composed of three PV strings of 23 modules each. These strings are connected to the grid via SB5000TL-21 inverters. These inverters are equipped with a monitoring system that collects the whole electrical parameters: Energy, Power, Current, Voltage, as well as, the modules temperature. The modules specifications at standard conditions are listed in (Table 1).

Fig. 5. Photo of the Solar Test Facility, 100 kWp different PV technologies installed at the Green energy Park (GEP), Benguerir, Morocco

Fig. 6. The studied monocrystalline PV system

Table 1. Main characteristics of the PV modules.

Parameters	Monocrystalline
Rated power (W)	240
Vmpp (V)	30.4
Impp (A)	7.9
Voc (V)	37.3
Isc (A)	8.3
Power Temperature coefficient (%/°C)	-0.41
Voltage Temperature coefficient (%/°C)	-0.30

During the testing period from August 2017 to February 2018, One strings was cleaned two time per week; while, the second one was not cleaned throughout all the test period. The cleaned string is used as a reference to calculate the soiling ratio, the difference in energy and the difference in the performance ratio with the following formulas:

$SR = \frac{Id}{Ic}$ (1)

$\Delta E = Ec - Ed$ (2)

$\Delta PR = PRc - PRd$ (3)

Id: The courant of the un-cleaned module.

Ic: The courant of the cleaned module.

PRd: The performance ratio of the un-cleaned module.

PRc: The performance ratio of the cleaned module.

Ed: The energy of the un-cleaned module.

Ec: The energy of the cleaned module.

4. Results and discussion:

4.1. Weather parameters:

Fig.7 shows daily total in-plane solar insolation on the PV modules measured from August 2017 to February 2018. The daily average total solar insolation varies throughout the test duration. These values varied between (8 kWh/m²) as maximum, (0.6 kWh/m²) as minimum and an average of 6.01 kWh which mean that our site has a good solar potential.

Fig.7 shows also the daily precipitation variation from August 2017 to February 2018. From the figure, we can clearly observe that the rainfall during the experiment is divided into two main periods, the first one from August the 17th to November the 29th (called dry period) in which the precipitation records are almost zero, and a second one from November the 30th to February the 26th a period with precipitation records reaching 26.1 mm. This period considered as a rainy period.

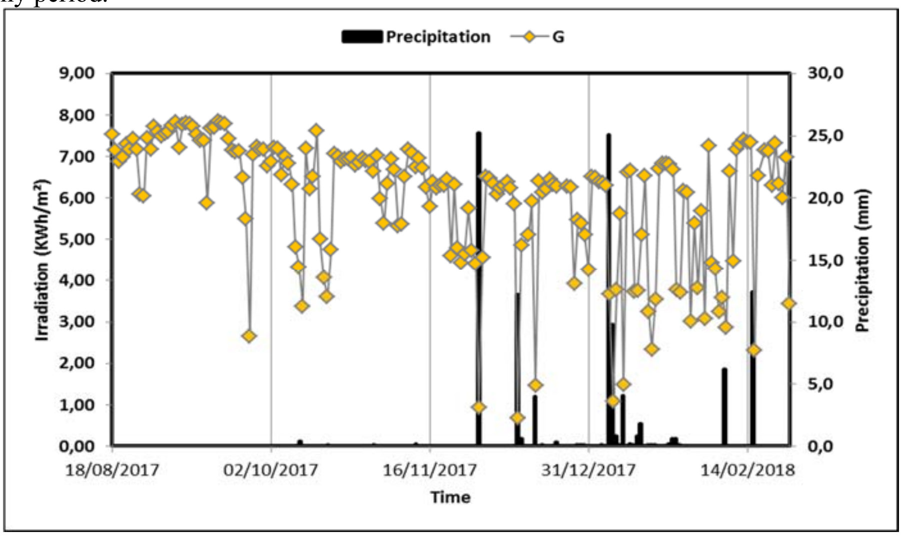

Fig 7. The energy of the dusted and cleaned strings in function of the difference in energy

4.2. Energy and performance ratio (PR):

The energy of cleaned and dusty strings is plotted in Fig.8 as a function of the difference in energy calculated from Eq. (2) for the system under investigation. After evaluating the system's data records from August the 18th to February the 26th, we noticed that the production of the dusted string is always lower than the cleaned one during the the dry period. Indeed, for a not rainy day (November the 20th for instance) the energy produced by the cleaned string was about 30.57 kWh, while, the dusted one produced an energy of 25.99 kWh, which is lower by 4.56 kWh than the other. However, during the rainy days the two strings have the same production (in December the 4th for example) the energy produced by the cleaned string were of 31.85 kWh, while, the dusted one produced an energy of 31.82 kWh. In some days we notice a decrease in the energy difference due to some specific events. In fact, in September the 15th the energy difference was about 3.82 kWh due to a manual system cleaning of the whole system. Similarly, in October the 11th and November the 30th a drop of 2.8 kWh and 4.8 kWh respectively was measured due to rainfall.

During the dry period from the 17th of October until the 29th of November, the energy loosed due to soiling reaches in total 124 kWh, which is equivalent to 2.7 KWh/day in average.

Regarding the rainy period (from the 30th of November to the 26th of February), the energy loosed due to soiling reaches an average of 0.007 kWh/day.

We need to mention that the system was disconnected, thus, non-operational on the 13th, 19th, 23rd of December and the 17th and the 24th of February.

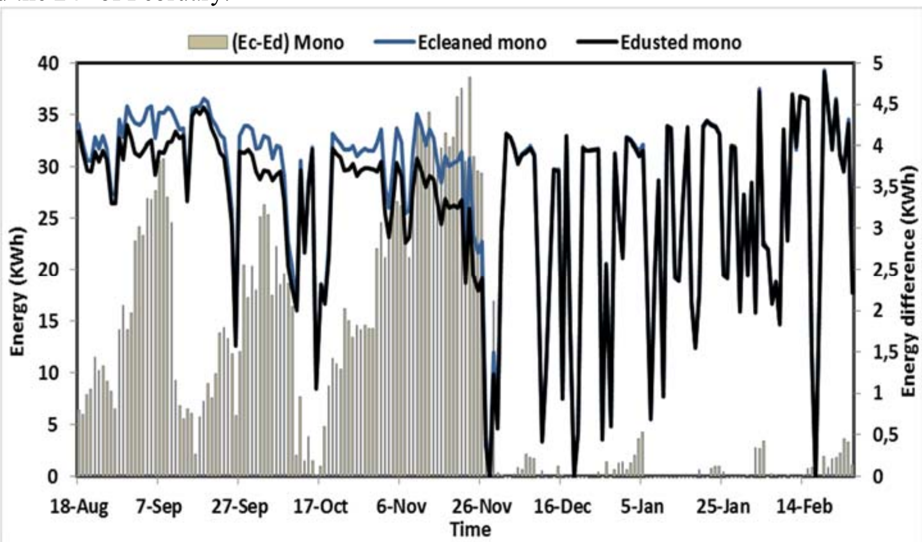

Fig. 8. The energy of the dusted and cleaned strings in function of the difference in energy

The performance ratio is a parameter usualy used to evaluate and compare the performance of the PV systems with differents sizes and locations, but in our case we used the performance ratio difference as a parametre to evaluate the effect of soiling on the PV performance.

Fig. 9 shows the Performance Ratio difference (ΔPR) between the soiled and the cleaned system. This parameter is calculated from Eq. (3). As it can be noticed, and simelarelly to the soiling rate, in September the 12th the PR drop was of 10%; this is due to a cleaning of the whole system, in October the 10th and November the 30th a drop of 8.3% and 15.3% in performance ratio difference was respectively obtained due to rainfall.

During the dry period from the 17th of October to the 29th of November, the performance ratio loosed due to soiling reaches ~ 0.3% in average and 15.3% as maximum.

During the rainy period from the 30th of November to the 26th of February, the performance ratio loosed due to soiling reaches ~ 0.025% as average and 1.8% as maximum.

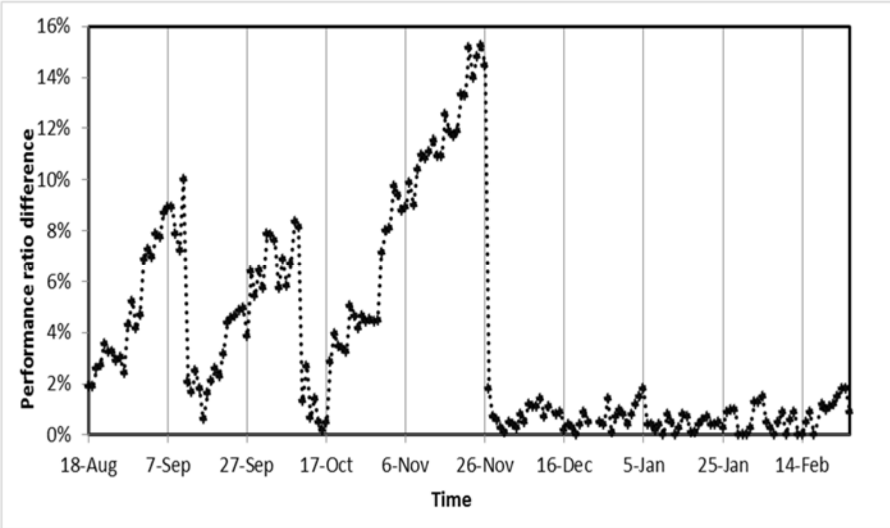

Fig 9. The performance ratio difference of the system

4.3. Soiling ratio:

As mentioned above, the soiling rate (SR) was calculated from Eq. (1) using the average of the courant from 11:00 AM to 1:00 PM for the dusted and cleaned strings. From Fig.10 it is noted that the rate of soiling varies in a regressive way from 1 (clean state). We notice that during the first period from August the 18th to September the 15th, the two strings were not identical (SR=0,96) for this reason we decided to clean the whole system (clean string and dusty string) and we can clearly observe that in September the 16th (the day after cleaning) the SR$\approx$1. In October the 16th and November the 30th the SR resumes the initial value (SR=1) due to precipitation. A maximum value of 0.84 was obtained in November the 26th equivalents to 16% from the system performance.

During the dry period from October the 17th to November the 29th, the daily soiling ratio reaches an average of ~ 0.32%/day, during the rainy period from the 30th of November to the 26th of February; the daily soiling ratio reaches an average of ~ 0.02%/day.

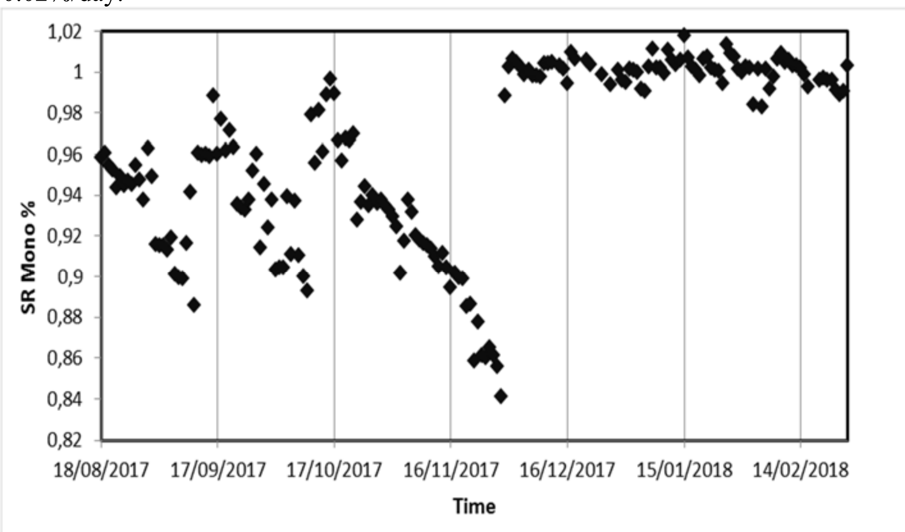

Fig. 10. The soiling ratio of the system

5. Conclusion:

The aim of this paper is to present the effect of dust accumulation on the crystalline photovoltaic modules performance in the semi-arid conditions. For this reason, an experimental study was carried out to calculate the soiling ratio, the energy difference and the performance ratio difference of a monocrystalline photovoltaic system. The key results of this study are summarized below:

- The dusted string provides lower energy than the other with ~ 2,7kWh/day as an average during the dry period and 0.07kWh/day during the rainy ones.
- The performance ratio difference (ΔPR) shown a maximum of 16% as during the dry period and 2% during the rainy ones.
- The daily soiling ratio reaches an average of 0.32%/day during the dry period.
- During the experiment period, the main soiling sources were a construction and a phosphate mining site lose by Green Energy park.

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