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STUDY OF SOILING ON PYRANOMETERS IN DESERT CONDITIONS

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Abstract

This work presents a study of the degree of soiling on pyranometers in Qatar, a region with high amounts of dust in the atmosphere. The experiment was performed during several months including a dusty season. It consists of using two pyranometers to measure the global horizontal irradiance: one of the pyranometers was considered the reference sensor and was cleaned on a daily basis, and the other pyranometer was used as the testing one, on which different frequencies of cleaning were tested. In order to evaluate the losses in the measurements due to dust/dirt accumulation on the sensor dome, the ratio of the daily average of global horizontal irradiance measured by both sensors was calculated and analysed in function of the time passed after the last cleaning of the testing sensor. From day to day, the changes in this ratio are between 0.3% and 0.5% *per day* depending on the soiling environment of each season, with increasing changes towards summer. The relative errors (RMSE and bias) of the output of the testing sensor as compared to the reference one were also studied and show a linear increase with the time passed since the last cleaning, for the period under study. It is concluded that a schedule of daily, or every 2 days, cleaning of the pyranometer dome is advisable in order to avoid noticeable errors in the measurements. This study helps to develop an adapted quality assurance programme for sensors installed at remote sites in the desert, including an adapted cleaning schedule which takes into account the local environmental conditions.

Keywords: *solar radiation, solar measurements, pyranometers, soiling, GHI.*

1. Introduction

As solar-based projects multiply across the planet, the need for high-quality assessment of the available solar resources also increases. Solar resource assessment is needed throughout the lifetime of solar power projects, from the prefeasibility studies to the operation of the final system. Knowledge of the historical (long-term) solar climatology at the selected site is fundamental for plant sizing and bankability studies, and such historical solar data are usually obtained with the aid of long-term satellite observations site-adapted with direct, ground measurements. Real-time solar input data during the plant operation goes directly into the calculation of plant performance, as well as into forecasting methodologies. It is, therefore, evident that the solar measurements have to be accurate and trustable enough for the cited purposes.

Currently, the most accurate measurements of the solar resource can be obtained with thermoelectric radiometers. For projects based on photovoltaic (PV) technology, the solar resource is usually measured on the horizontal plane, in the form of the so-called global horizontal irradiance, using thermopile pyranometers. This type of radiometers is the one recommended by the International Organization for Standardization (ISO) and the World Meteorological Organization (WMO), to measure the global solar radiation. Pyranometers typically have one or two curved optical glass domes covering the sensor for protection and reduction of dirt or rain drop deposition. When they are used for solar resource assessment studies, the radiometers are usually installed at remote sites and left unattended to achieve continuous measurements. The instrument is exposed to the weather conditions and might accumulate substantial amounts of dirt on its dome, especially in desert

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regions; this is problematic since it affects the quality of the measurements and thus the resource assessment studies and solar projects relying on these data.

To obtain accurate measurements, two checks should be done daily on the sensors: alignment and cleaning of the dome. However, when the sensor is located at remote sites, it is usually difficult to follow this ideal maintenance schedule or at least to control that it is done the right way. Therefore, the study and quantification of soiling will result in a better management of a solar radiation network distributed across remote sites, and will help in terms of setting optimum rules for the frequency of sensor cleaning and for correcting the data before final processing.

While studies of the effect of soiling on PV panel performance are common (see, e.g., Urrejola et al., 2016; Maghami et al., 2016; a recent PV soiling study was carried out in Qatar by Abdallah et al., 2016), sensor soiling studies are not so abundant, but several examples can be found, like Hammond et al. (1997) in Arizona, Maxwell et al. (1999) in Saudi Arabia, Geuder and Quaschning (2006) in Spain and Morocco, Pape et al. (2009), and Wolfertstetter et al. (2014) in the north of Africa. Most of these studies focus on only determining a sensor cleaning frequency for specific sites; Geuder and Quaschning (2006) propose a method to correct for soiling which, however, requires the measurement of the beam, global and diffuse radiations and, along similar lines, Pape et al. (2009) describe an additional accessory to determine soiling rates. In a report of IEA SHC Task 46 (Wilbert et al., 2015), the soiling of a rotating shadow band irradiometer (RSI) and a pyrheliometer was studied during a period of one month in Almeria, Spain. After one month of not cleaning both sensors at this location, they found that the relative error of the uncleaned pyrheliometer follows a linear trend with an increase of around 0.7% per day, whereas the relative error of DNI measurements of the uncleaned RSI varies within the range of the reference uncertainty of ±2 %.

This work focuses on the study of pyranometer soiling and its characteristics in a region where dust is highly present in the atmosphere, and dust storms occur frequently. Qatar is embarking on its journey of using solar energy for power production and, to measure its solar resources, a network of 13 solar radiation monitoring stations will be deployed throughout the country (Mohieldeen et al., 2015). Due to the location of the stations in the desert, the sensors will be highly susceptible to soiling, thus affecting the accuracy and reliability of the measurements. In the present work, a methodology is described to determine the effects of soiling on the output of the pyranometer.

2. Methodology

The total or global horizontal irradiance (G) can be measured using a thermopile pyranometer mounted on a horizontal surface. In this work, two Kipp & Zonen CMP11 pyranometers mounted on the same horizontal platform, each provided with a ventilation unit and located at the same site in Doha, Qatar, are used (Perez-Astudillo and Bachour, 2014); one of the radiometers is considered the reference, on which the cleaning and alignment check are done on a daily basis, and the other pyranometer is used for testing, where only the alignment check is done every day, and the cleaning frequency followed different scenarios. During the first week of the experiment, both sensors were cleaned on a daily basis for calibration purposes to ensure that for the soiling study both sensors provide the same measured values. For the next three consecutive weeks, the testing sensor was left without any manual cleaning, only somewhat washed by some rain events. Afterwards, the cleaning frequency of the testing sensor varied following the schedule in Table 1, which shows the days when this sensor was cleaned. Note that for the month of July, the *reference* sensor was not cleaned from the 3rd until the 14th of July; these days are excluded from the data analysis of this soiling study.

Tab.1: Cleaning schedule of the testing sensor from March until September 2016. Note that the reference sensor was cleaned every day including the days shown in the table. *See also note for July in the text.

Dates of cleaning						
March	April	May	June	July*	August	September
12	1	--	--	2 & 15	1 & 21	25

It can be seen from Table 1 that the longest period in which the test sensor was left without cleaning is from

April through June (90 consecutive days without cleaning), followed by the period from August 21 until September 25 (35 days). The shortest period was in the second half of July (16 days). In March and August, the testing periods were of 19 days. For simplicity, the testing periods are called herein: A (Mar), B (Apr-Jun), C (Jul), D (1st half of Aug) and E (Aug-Sep). A future scenario consists of not cleaning the sensor for several months to test whether the losses due to soiling will reach a plateau.

The analysis of the difference between the two measurements under the different cleaning regimes stated above will be used to quantify the soiling of pyranometers and to understand its characteristics and the change of associated errors with time. This analysis will consequently lead to the establishment of independent benchmarks and procedures to control the data and the sensors, due to soiling in desert regions.

3. Results and discussions

3.1. Calibration of the two sensors

Since the current soiling study relies on the measurements of two independent sensors, it was deemed necessary to calibrate the sensors relatively to each other, in order to eliminate sources of errors related to a drift or variations in the response of the sensors and to ensure that for the same conditions, the data from both sensors are comparable.

The calibration was performed using the days when both sensors were cleaned, which consist of all days during the first week of the experiment and several other days representing different seasons across different months: one day in April, two days in July, two days in August and one day in September. Fig. 1 shows in black, for the calibration days, the 1-minute values G_test measured by the testing pyranometer (the one to be kept without cleaning afterwards) versus G_ref, measured by the reference pyranometer (the one used as a control, with daily cleaning). The testing pyranometer slightly underestimates G. This underestimation can be fitted using a linear function, shown in blue on the graph. The linear fit relates G_test to G_ref through the following equation:

$$G\_test = 0.996547 * G\_ref - 3.99292 \qquad \text{(eq.1)}$$

Equation 1 was then used to calibrate G_test, for the following data analysis.

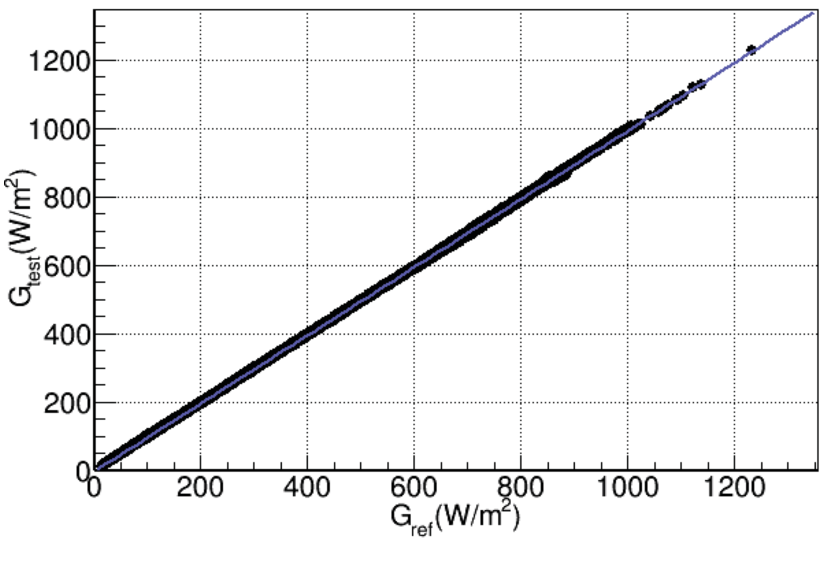

Fig. 1: Comparison of the G values (W/m2) measured by the testing and reference pyranometers.

3.2. Effect of pyranometer soiling on measured G

In order to study the effect of the soiling with the time passed since the last cleaning of the test sensor, the errors in terms of daily relative root mean square error (rRMSE) and relative bias (rBias) were studied for each of the testing periods. Fig. 2 and Fig. 3 show, respectively, rRMSE and rBias as function of time.

In Fig. 2, each point represents the relative RMSE between the two sets of 1-minute measurements during one day. It should be noted that the errors are calculated after calibration of the testing sensor against the reference one, as described in Section 3.1. The relative RMSE is calculated as

$$rRMSE = \frac{\sqrt{\frac{\sum_0^N (G\_test - G\_ref)^2}{N}}}{G\_ref_{mean}} \; , \qquad \text{(eq.2)}$$

where G_ref and G_test are the 1-minute values within one day, measured respectively by the reference pyranometer and the testing one. N is the total number of included minutes during that day and G_ref_{mean} is the mean value of G_ref during that same day.

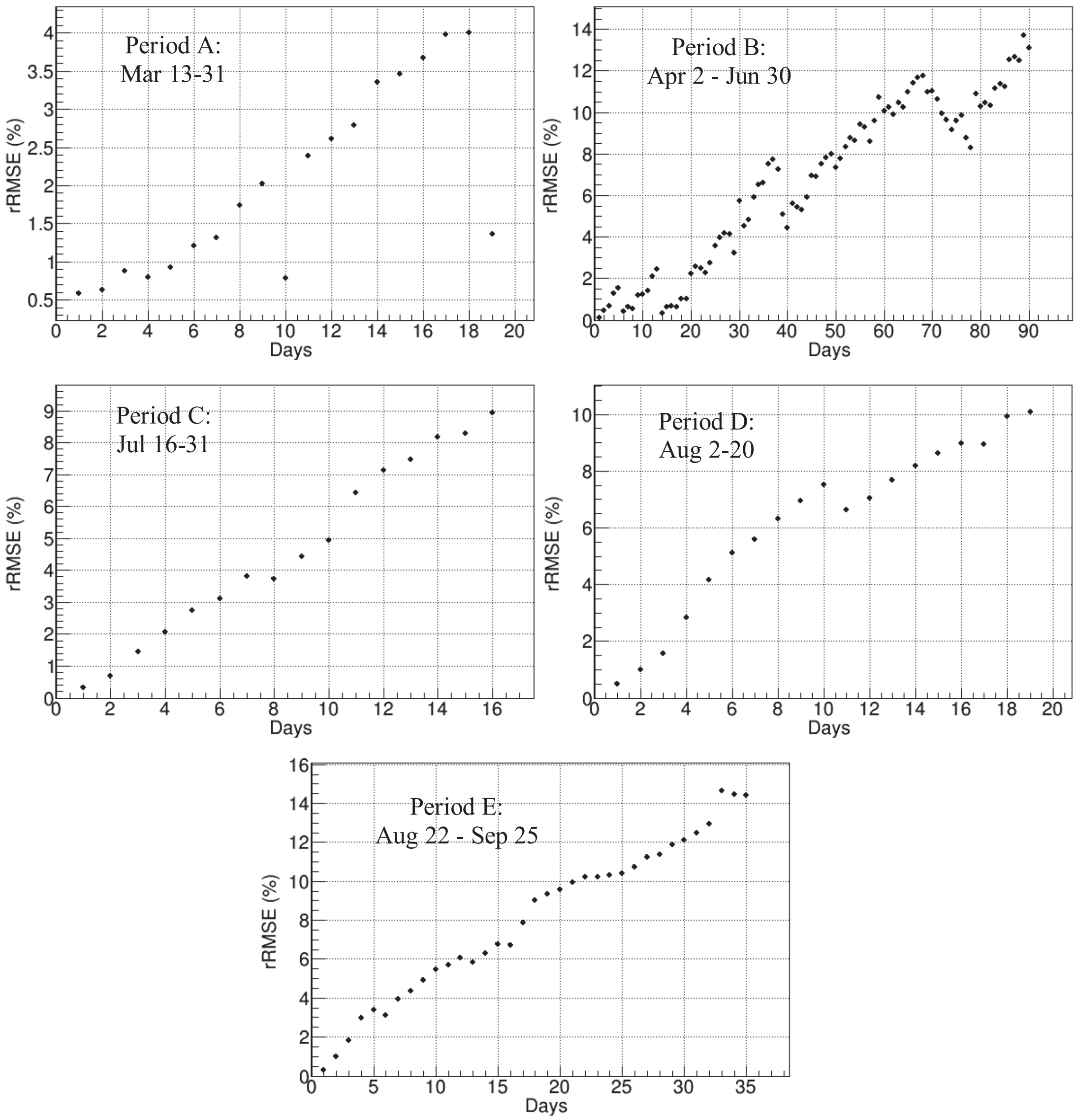

Fig. 2: Daily values of relative RMSE between G_test and G_ref for several days after cleaning the testing sensor, for different testing periods (shown on each of the plots).

It can be seen that for each of the testing periods the error due to soiling is continuously increasing with time; points showing deviation from the increasing trend correspond to rain events. The magnitude and speed of the increase in the error are different between the testing periods and depend on the season. For instance, the error in period 'A' grew at slower rate than in periods 'D' and 'E': it reached 4% after 17 days since the last cleaning in period 'A', whereas in period 'E' it reached the same level after 7 days. This is most probably due to more stable weather conditions, i.e., mostly clear days, in the summer months, but also due to the increasing dust levels in the atmosphere during summer. It is to be noted that for each of the testing periods, the error due to the pyranometer soiling starts increasing from 0 (see Fig. 2 and 3), which means that the calibration factors were the same at the start of each period; in other words, after each cleaning event of the testing sensor, the signal is brought to the same level of the signal of the reference sensor.

In order to better understand this behaviour and be able to compare the differences in rRMSE within different periods, the average rRMSE for a span of 15 days after the last cleaning was calculated for each of the testing periods and is shown in Table 2.

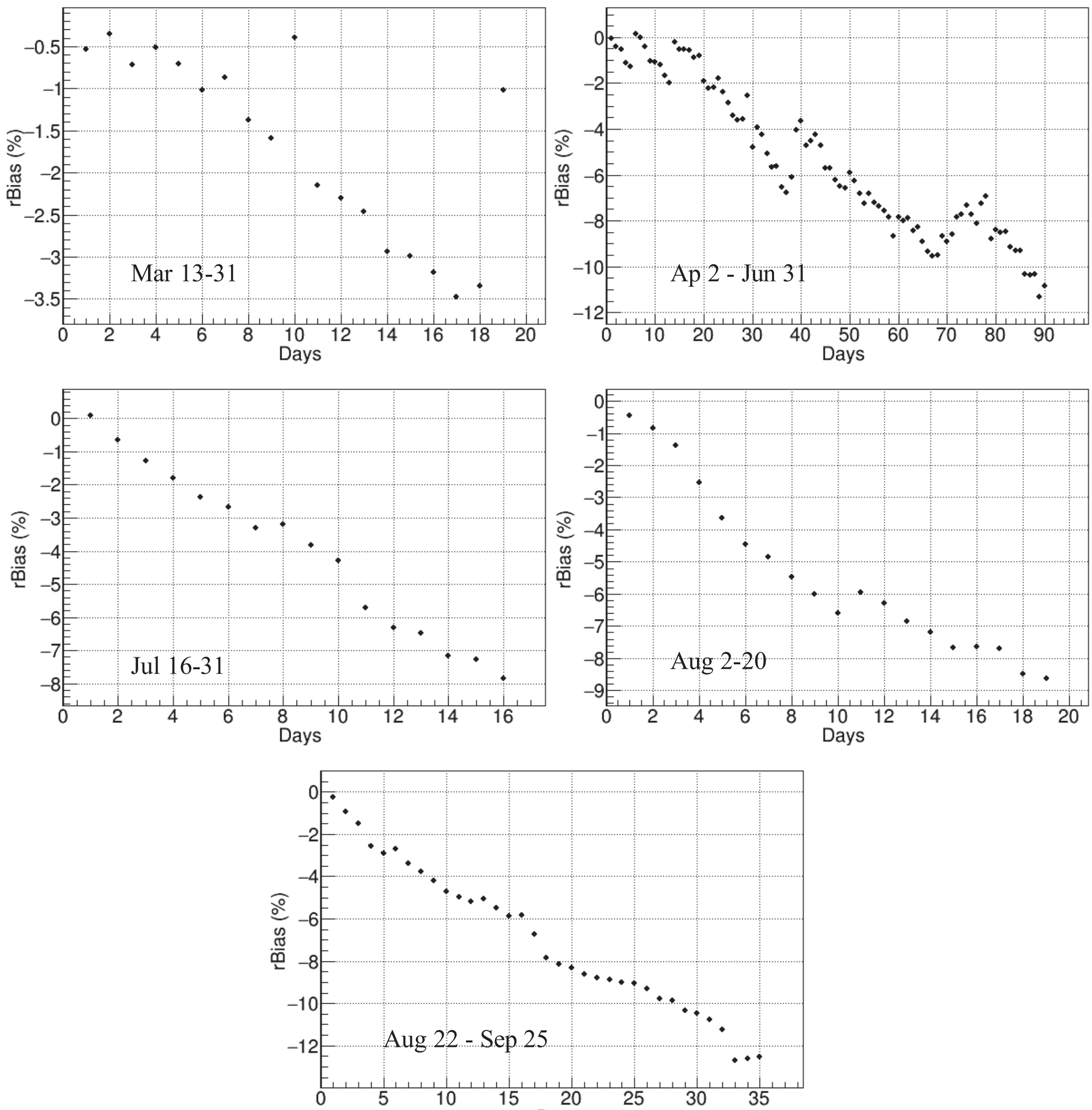

Fig. 3: Daily averages of relative Bias between G_test and G_ref for several days after cleaning the testing sensor, for different testing periods (shown on each of the plots).

Tab.2: Average of relative RMSE during 15 days after cleaning the testing sensor, for each of the testing periods.

rRMSE (%)				
March	April	July	Aug (first half)	Aug-Sep
1.71	0.99	4.32	5.32	4.13

Comparatively, it is noticeable that the averaged rRMSE during the first 15 days since the last cleaning is higher in the summer months. The low value of the averaged error in April is due to the frequent rainy days during this period, which resulted in a low average of rRMSE.

For comparison purposes also, Table 3 shows the quantification of the level of increase of rRMSE per day due to soiling, for each of the studied periods. These values were determined by establishing a linear relation between rRMSE and the days since the last cleaning, separately for each period. Although finding the relation was not straightforward due to changing weather conditions, especially in period 'B', an average rate was calculated using different series of consecutive clear days. The dependency of the soiling effect on the season is clear: the average increase of rRMSE is lower in March and April and higher in July and August, when dust is more abundant in the local atmosphere.

Tab.3: Average increase in relative RMSE, per day, for each of the testing periods.

rRMSE/day (%)				
A	**B**	**C**	**D**	**E**
0.25	0.33	0.6	0.5	0.4

In Fig. 3, each point represents the relative bias error between the two sets of measurements during one day, calculated using Equation 3, after calibration of the testing sensor against the reference one.

$$rBias = \frac{\frac{\Sigma(G_{test}-G_{ref})}{N}}{G\_ref_{mean}} \qquad \text{(eq.3)}$$

As expected, rBias increases as a function of time and this increase more or less follows the trend of the rRMSE. This can be explained by looking closely to the plot in Fig. 4, which shows the relative bias of each 1-minute pair (G_test vs. G_ref) as a function of time for the testing period 'E'. For clarity, the data shown were limited to minutes between hours 9 and 14 (local time). It is clear that the mean relative bias increases with time, similarly to Fig. 3, but it is noted too that the amplitude of each individual U-shaped curve (corresponding to one day) also increases with time and remains more or less constant after a certain time. The shape of each day's rBias depends on the spatial distribution of dust on the dome, as dust accumulates more on the top than on the sides of the dome, thus obstructing more direct sunlight (resulting in larger bias) when the sun is higher in the sky. The increasing amplitude with time contributes to the growing trend of the relative daily RMSE (as seen in Fig. 2).

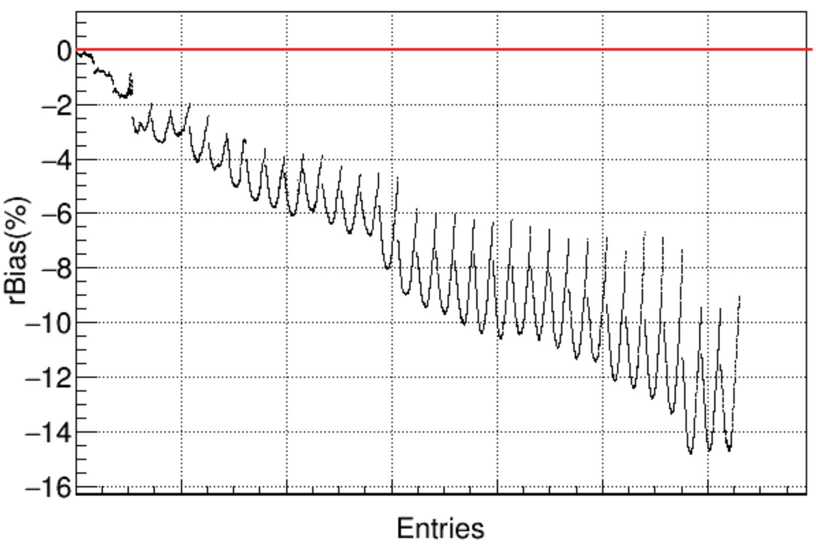

Fig. 4: Relative Bias of each one-minute value of G_test relative to G_ref for several days after cleaning the testing sensor, during the last testing period (22 Aug to 25 Sep).

Tab.4: Average change of relative bias, per day, for each of the testing periods.

rBias/day (%)				
A	**B**	**C**	**D**	**E**
-0.22	-0.3	-0.53	-0.43	-0.38

Table 4 shows the averaged increase per day of the relative bias due to soiling, for each of the studied periods. Similarly to the determination of the increase of rRMSE per day, this was determined by fitting a linear function on the plots in Figure 3, using consecutive clear days and excluding days with rain events. Here also, the rate of increase of the relative bias per day is higher in the summer months of July and August.

To obtain a quantitative evaluation of the loss in G due to sensor soiling, the ratio of the daily average of G_soil to G_ref (hereby called 'cleanliness') as a function of time since the last cleaning, is studied (shown in Figure 5, for period 'C'). The correlation between the cleanliness and time (the linear fit function shown in red) gives the value of the loss in output signal per day due to soiling. As in the previous cases, the loss was easily determined in periods of clear days. In periods with unstable conditions, it was determined using the average of the loss of one or several series of consecutive clear days (if found). As a result of this test, the loss per day in the global radiation due to soiling is around 0.2 to 0.3% in periods 'A' and 'B', from March to June, and is evaluated as 0.5% and 0.4% in July and August, respectively.

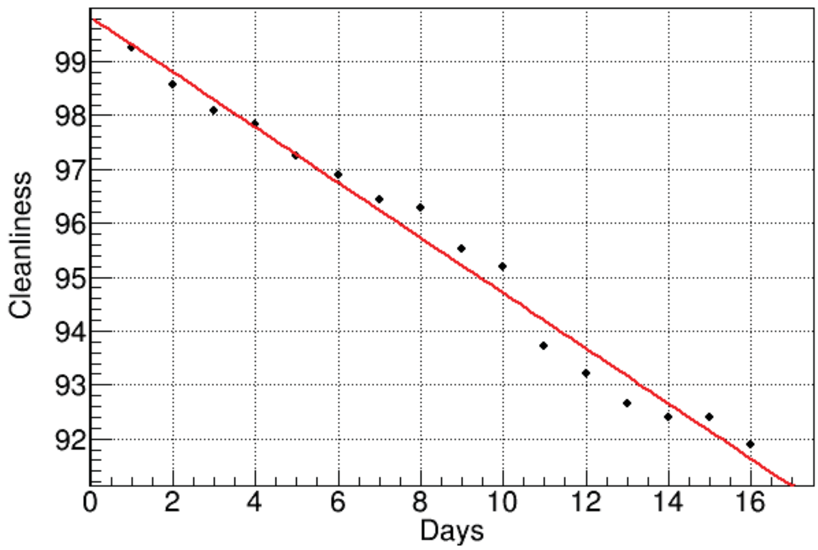

Fig.5: Decrease of measured global horizontal radiation per day due to sensor soiling, in period C. The red line is the fit of the cleanliness with time.

4. Conclusions

For the deployment of solar projects using photovoltaic systems, one of the key parameters to determine is the global horizontal irradiance, G, as part of the solar resource assessment studies for the project. G is usually measured on the horizontal plane using thermopile pyranometers. In this type of radiometers, the sensor is protected from the elements by a transparent dome, which only allows solar radiation to reach the sensor. Because the dome is exposed to the elements, it gets dirty, or soiled, as time passes, due to deposition of atmospheric dust and particulates, rain, snow, bird droppings, etc. This soiling obstructs the passage of sunlight to the sensor, resulting in erroneously low measurements, more obviously at locations with high amounts of dust in the atmosphere. Therefore, an important part of the routine maintenance of the sensor is the periodic cleaning of the dome. Ideally, this cleaning should be done daily; however, this is not always possible, for example, at remote unmanned sites, and also the costs (personnel, transportation, etc.) have to be considered, so in practice the instrument cleaning is commonly done at longer intervals, sometimes extending several weeks or even months. The optimal cleaning frequency depends on each site's conditions, which are highly variable depending on atmospheric and any other surrounding events.

In this work, the assessment of the soiling rate of pyranometers was evaluated using two sensors: one with daily cleaning and another one following a cleaning schedule with varying intervals. The results show that the measurement errors due to soiling increase linearly with time, and the increase varies depending on the weather conditions, with a seasonal dependency. The average increases in rRMSE and rBias are, respectively, around 0.4% per day and 0.37% per day, for the studied period.

The actual decrease in the signal due to accumulation of dust on the dome of the pyranometer is evaluated as around 0.2 to 0.3% per day for the winter season, and around 0.4% to 0.5% per day for the summer season. This shows that the effect of dust and soil on the pyranometer signal is not negligible in dusty environments even in short intervals, frequent cleaning of the glass dome of the instrument should be followed in order to avoid dust accumulation and consequently larger errors on the measured data. According to the analysis shown here, and in order to ensure low deviations from the correct measurement (on the order of 1 to 2 %) in dusty regions, the pyranometer dome should be cleaned daily, or every 2 days.

Although the results presented here cannot be universally applied due to varying soiling conditions between different sites, they may be useful in regions with similar weather conditions.

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