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CSP mirror soiling characterization and modeling

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ABSTRACT

Soiling stands as a major problem for solar energy conversion technologies, causing unwanted transmittance, reflectance and absorbance losses. In this paper, a TraCS (Tracking Cleanliness Sensor) is used to quantify soiling effect in a flat mirror and to calculate soiling rates between periods without rain. Environmental parameters such as vertical wind speed, air temperature, relative humidity and particulate matter in the atmosphere are used as predictors to model soiling. Relations and trends between input and output are analyzed using a simple linear regression model and also through an interaction model. Further investigation is performed with a neural network approach to assess its viability for this type of problem and also for comparison with the previous models.

1. Introduction

Soiling, the process of atmospheric particle settling on surfaces, is a general problem and leads to the need of cleaning, e.g. glass windows of skyscrapers, house cleaning, and nonetheless it is an obstacle for solar conversion technologies [1–7]. It is known that soiling is mostly a local phenomenon, which depends on with the amount of particles suspended in the atmosphere, as well as on environmental conditions. The rural region of Évora, Alentejo, Portugal (Southern Europe), has been under study regarding the effect of soiling in PV technology. The most severe seasons for soiling were identified [7], as well as occasional non-local effects [6]. However, there is a lack of studies regarding the effect of soiling in CSP compared to PV and none for this region or other similar rural areas, which provides a unique research opportunity. The direct effect of soiling in PV production is easier to investigate than in any CSP technology, due to it intrinsic simplicity. This is one of the reasons why CSP soiling studies are more scarce. It should be noted that measurements of mass accumulation and transmittance/reflectance losses on glass/mirror samples (in a static position, which is usual) can be used as in PV technology related results. However, a more realistic CSP study, might require samples to move throughout the day, to simulate the tracking associated with such systems. Despite this, there are already interesting studies about CSP soiling [8–11]. Additionally, a higher soiling impact is expected in CSP than PV, due to the fact that light goes twice through the soiling layer, which can lead to more scatter and therefore less useful irradiance (given the small acceptance angles of the concentrators). In fact, soiling will modify the light path, not only when it reaches the mirrors, but also as it exits them and also increase the internal reflections within the glass. Overall, this process will result in a soiling effect which is 5–10 times worst than in PV [12].

It is the goal of this paper to develop soiling prediction models using three different methods: (i) linear, (ii) linear with interaction terms and (iii) a neural networks type. The prediction of soiling has been shown to be very difficult, mainly because it is essentially an atmospheric process, which usually needs to take into account many environmental parameters, which makes the problem complex. The analysis will start with a linear relationship to assess variable's trends. A linear regression will also be tested with interaction terms to check if there is any relation between the output and interlinked predictors. However, since the process may be very complicated to solve explicitly, a neural network with 1 hidden layer was designed and the optimum number of neurons calculated through a similar process as in [13]. The objective is not only to try to find different models that fit the data well and can serve as prediction models, but also to evaluate possible trends and relations between the variables, which can be explained from a physical point of view.

2. Soiling effect and environmental measurements

2.1. Measurements setup

Measurements of soiling effect on mirror reflectance were performed using a TraCS from CSP Services (Germany) mounted on a SOLYS 2 sun tracker, from Kipp & Zonen (Holland, uncertainty ≤ 2% for pyrheliometer hourly values); vertical wind speed was retrieved using a WindMaster Pro 3-Axis Anemometer from Gill Instruments (UK,

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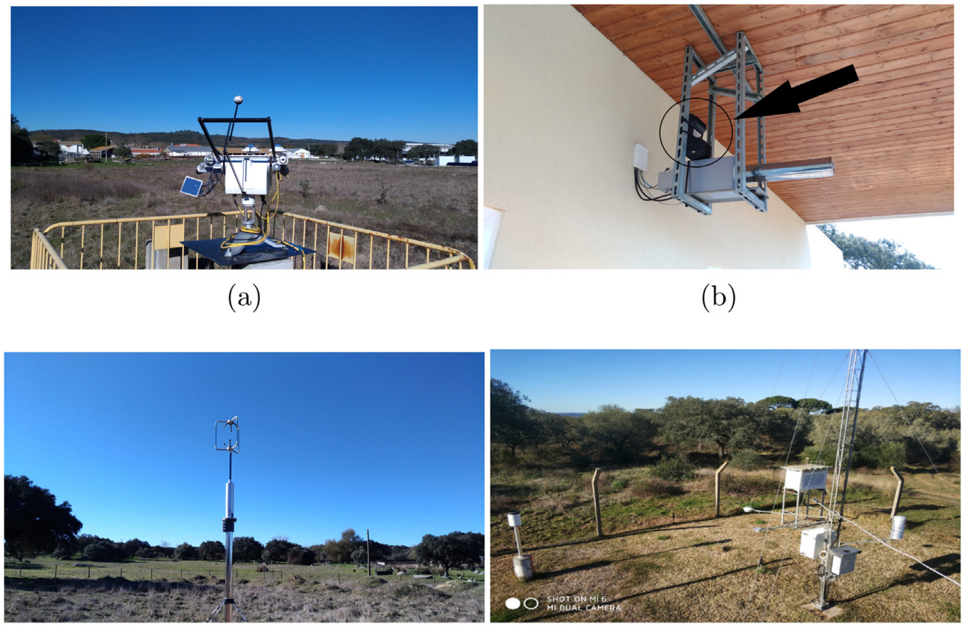
(a) (b) (c) (d)

Fig. 1. Measuring instrumentation: (a) TraCS and SOLYS2; (b) Dylos DC1100 Pro; (c) WindMaster Pro; (d) Meteorological station.

uncertainty ≤ 1.5% RMS); particulate matter measurements were taken with a DC1100 Pro from Dylos Corporation (USA, uncertainty ≤ 10%); temperature, relative humidity and precipitation were measured at a nearby meteorological station (≈ 750 m) with a Thermo-Hygrometer (Thies Clima, Germany, with uncertainty ≤ 3% for relative humidity and 0.5 °C for temperature) and a Tipping Bucket Rain gauge from RM Young (USA, uncertainty ≤ 2%), respectively. Below, in Fig. 1, are presented the instruments referred before:

It should be noted that soiling effect is calculated through comparison between the direct normal irradiance, I_b, and the irradiance measured by a second pyrheliometer, I_b^r, reflected by the TraCS's mirror [14,15]. This mirror is rotating and performs a full revolution every 10 min and due to the fact that sun spectrum is variable throughout the day, daily means were calculated using data around solar noon. This process will be explained afterwards.

2.2. Soiling index

The measurement campaign started in June 2017 and lasted until the end of that year. The mirror was cleaned at the beginning of every month from June to August and then left untouched, due to the start of the raining season. During Summer, cleaning was performed to avoid soiling saturation, above which no measurements could be done.

The soiling index, λ, here defined as the normalized ratio between the reflected direct normal irradiance, I_b^r, from the mirror and measured direct normal irradiance, I_b. The soiling index is represented in Fig. 2a and given by:

$$\lambda = 1 - \frac{\rho}{\rho_0}, \tag{1}$$

where $\rho = \frac{I_b^r}{I_b}$. The parameter ρ_0 corresponds to the maximum weighted reflectance measured with the mirror cleaned. This value was calculated by the manufacturer after a series of tests and represents the clean scenario mean reflectance.

The outcome of Eq. (1) is a null value in the absence of soiling, and as the particle deposition increases the soiling index also increases.

The effect of manual cleaning done to the mirror until September can be observed. It should be noted that the results derived from cleaning are not always the same, probably due to improper cleaning, as well as slight changes in mirror positioning, which can influence the irradiance that strikes the pyrheliometer. However, for this study, relative values are more important than absolute ones, since the soiling of the next day will be compared to the previous one.

Regarding the data, it is seen that Summer is indeed the worst season for soiling; perhaps an exception should be made for Spring (the sensor was not working yet), when high soiling values were detected for PV technology [7]. Later, in November and December, after rain and dew formation has been detected regularly (more than during Summer), λ recovered to low values.

2.3. Environmental parameters and methodology

Daily means were calculated following the schematic in Fig. 3. Two different days are represented, where the yellow curve corresponds to typical TraCS measurements. The mean of the soiling index of the day before is represented by λ_i, while for the next day it is given by λ_{i+1} and it is calculate around solar noon, represented by the black lines. The difference between the previous day and the next day is represented by $\Delta\lambda$, see Eq. (2).

$$\Delta\lambda = \lambda_{i+1} - \lambda_i \tag{2}$$

This parameter represents an increase of soiling from one day to the following, if it is positive, and a reduction of soiling, if it is negative. Particulate matter values, $PM_{0.5-2.5}$, correspond to a 24-h mean, from 14 h of the previous day to the next day, as well as vertical wind speed, VWS. Temperature, T, and relative humidity, RH, are a result of the mean from 9 h of the previous day until 6 h of the next day, see Fig. 3. Since $PM_{0.5-2.5}$ measurements have no RH compensation, all $PM_{0.5-2.5}$ values (minutely scale) corresponding to RH above 65% were removed, which implies that for some nights there are possibly no data for a few hours. To characterize the night period, both T and RH were used, which are also important for dew formation phenomenon, as well as hygroscopic growth [16]. Periods with precipitation were removed, since it is seen that is has a cleaning effect and the interest here is to study other environmental parameters that are possible interlinked with soiling effect.

Environmental parameters are presented in Fig. 4. It can be seen that the particulate matter, in Fig. 4a, which represents particulate