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Anti-soiling coating performance assessment on the reduction of soiling effect in second-surface solar mirror

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ABSTRACT

Soiling represents a major problem for CSP plants, since the accumulation of particles onto the reflective surface cause absorption and scattering of solar irradiance, leading to a significant decrease in the mirrors' reflectance. Such problem can be amplified, particularly in CSP plants that are installed in semi-arid or arid regions which possess a high direct normal irradiance availability, prone to higher particle deposition due to sand storms, red rain events and, in general, higher atmospheric particle concentration. As means to reduce the amount of dust adhering to the mirrors, anti-soiling coatings are being developed to reduce particle deposition, minimizing maintenance costs due to cleaning processes, leading to an enhancement of energy production. In this paper, a Tracking Cleanliness Sensor was used to compare the Soiling Index between a set of coated and uncoated mirrors, which were left outdoors to naturally accumulate soiling in two different positions, horizontal and tilted 45°. The anti-soiling coating was developed by a partnership between RIOGLASS and IK4-TEKNIKER. Moreover, a simple economical model is proposed here for different possible scenarios regarding the coating used.

1. Introduction

Soiling, i.e. particle accumulation onto the surfaces of solar power systems, can lead to significant energy losses (Adinoyi and Said, 2013; Boyle et al., 2015; Deffenbaugh et al., 1986), due to absorption and scattering of the incident solar irradiance (Conceição et al., 2019; Conceição et al., 2018; Ricardo Conceição et al., 2018c, 2018b; Piedra et al., 2018). Concentrated Solar Power (CSP) plants require clear-sky, direct normal irradiance (DNI), to achieve high temperatures in order to maintain an efficient operation of the CSP plant. For this reason, the reflectance of CSP mirrors is directly related to the power plant's output, having an important role in the optimization of CSP systems.

As a consequence of soiling effect, the mirror's reflectance loss has a direct impact on the plant's final revenue (Cohen et al., 1999). Unfortunately, severe weather conditions, such as dust storms (especially if followed by light rain), can significantly reduce reflectance (Kennedy, 2007). Moreover, dew and dust acting together can strongly enhance particle cementation to the mirror surface (Ennaceri et al., 2016). Thus, regular cleaning processes constitute a significant part of the Operation and Maintenance (O&M) tasks and costs, increasing the annual operation expenditures (OPEX) (Cohen et al., 1999; Fernández-García et al., 2013). According to the National Renewable Energy Laboratory (NREL), a 5% decrease in the specular reflectance would lead to a drastic increase of 5% in the levelized cost of electricity (LCOE) (Cole et al., 2017). Therefore, the development of anti-soiling coatings, as well as other water-free methods, to decrease soiling are needed in semi-arid and, particularly, in arid regions where this effect is more severe (Conceição et al., 2018) and where there can be high water scarcity levels.

With this objective in mind, the WASCOP project brought together RIOGLASS (a Spanish CSP mirror manufacturer) and IK4-TEKNIKER (a Spanish R&D institute) to develop a new type of anti-soiling coating. It is a hydrophilic and photocatalytic anti-soiling coating, which, according to (Aranzabe et al., 2018), has the particularity of having a longer durability relating to common coatings presented in the literature, thus having good prospects to reach the market in a few years'

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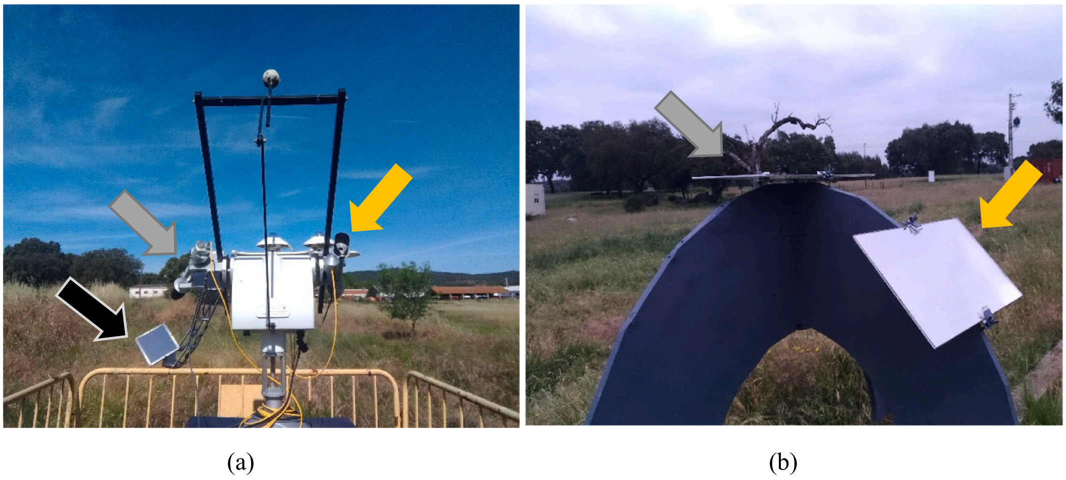


Fig. 1. Measurements setups: (a) TraCS apparatus, with the black arrow showing the location where the mirror sample is placed, while the grey arrow points to the pyrheliometer measuring the reflected irradiance from the mirror, and the yellow one points to the pyrheliometer measuring the direct normal irradiance (DNI); (b) Structure where the two samples, horizontal (grey arrow) and tilted 45° (yellow arrow), are held to accumulate soiling naturally. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time-scale. However, substantial experiments need to be performed on the coating's performance using different methodologies and considering different regions with potential for CSP implementation. For this reason, the experimental facilities of the Renewable Energy Chair (REC), University of Évora (Portugal, southern Europe) in the *Herdade da Mitra* near Valverde, Évora (38° 32′N, 8° 01′W), denominated *Plataforma de Ensaio de Colectores Solares* (PECS), represent an excellent opportunity to test coatings under a rural environment (e.g. most Spanish CSP plants are located in such areas), which also has one of the highest DNI availabilities in Europe (Lopes et al., 2018; Šúri et al., 2009). The objective of this study is to assess the performance of the anti-soiling coating for CSP second-surface mirrors in this region, using the methodology developed there (Ricardo Conceição et al., 2018a), to cut down maintenance costs due to cleaning processes. Additionally, a simple economic analysis is presented to explore possible scenarios for the use of such coating.

The paper is organized as follows: in Section 2 the methodology used is explained; in Section 3 the experimental results and discussion are presented along with an economic analysis; in Section 4, conclusions, as well as future work propositions, are presented.

2. Methodology

2.1. Sample preparation

The anti-soiling coating tested is Titania-based in the anatase form. It is initially applied through a wet-chemical technique over the glass. Once deposited, a conventional heat treatment on the glass allows the formation of a chemical covalent bond between the coating and the glass. According to Aranzabe et al. (2018), this results in a highly durable and homogeneous dense coating, also showing excellent anti-soiling properties due to its hydrophilic behavior.

To evaluate the coating efficiency, 300 × 100 mm glass samples were partially coated (half of the sample coated and half of the sample uncoated) by spray-coating and then thermally treated. The reflective layer was deposited afterwards on the back side of the glass. The coating thickness was in the range of 100–150 nm. The coating has photocatalytic properties being capable of degrading different pollutants. The hydrophilicity of the TiO_2 surface is induced by ultra-violet radiation (UV) and was measured using a goniometer after 24 h of UV exposure, the contact angles being 13° for the coated reflector and 45° for the uncoated reflector. It should be noted that these tests were not performed by REC, but by IK4-TEKNIKER and RIOGLASS.

2.2. Measurement setup

Measurements of soiling effect on mirror reflectance were performed using a Tracking Cleanliness Sensor (TraCS) from CSP Services (Germany) mounted on a SOLYS 2 sun tracker, as shown in Fig. 1a, from Kipp & Zonen (Holland, with an uncertainty 2% for pyrheliometer hourly values) in the PECS facility. The TraCS apparatus is composed by two pyrheliometers and a frame where mirror samples can be deployed. One pyrheliometer is always pointing towards the sun, measuring the beam of the Suńs disk on a normal surface, i.e. DNI, while the other one points backwards to the mirror sample and measures the irradiance being reflected by it. This set-up allows the calculation of the ratio between these two measured variables, see Fig. 2 for more details. This type of measurement allows to quantify the loss of reflectance due to soiling, and to evaluate it directly with the available solar irradiance, thus including a full solar spectrum response (which cannot be obtained with commercial portable reflectometers).

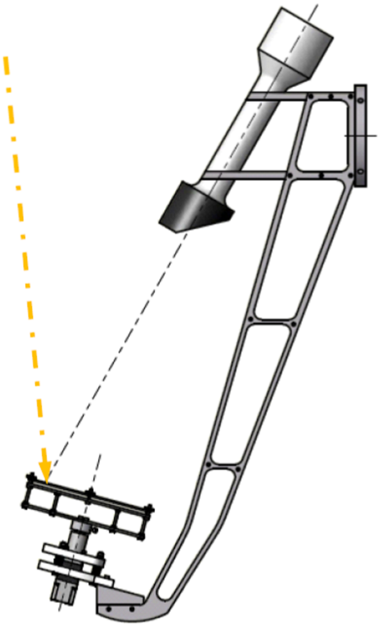


Fig. 2. TraCS apparatus in detail, taken from: http://www.cspservices.de/media/csps/CSPS-DLR-TraCS-1510.pdf.

As previously mentioned, the soiling effect is calculated by comparing the DNI, I_b (i.e. measured by the pyrheliometer pointing towards the sun), and the irradiance reflected by the mirror installed on the TraCS, I_b^r (i.e. measured by the pyrheliometer pointing backwards to the mirror). In this context, the Soiling Index, λ, can be defined as the normalized ratio between I_b^r and I_b, as given by Eq. (1):

$$\lambda = 1 - \frac{\rho}{\rho_0}, \quad (1)$$

where $\rho = \frac{I_b^r}{I_b}$. The parameter ρ_0 corresponds to the weighted reflectance when the mirror is cleaned. The Soiling Index fluctuates from 0 to 1, where a value of 0 corresponds to a completely cleaned mirror, while the value of 1 corresponds to a completely soiled surface. It should be noted that this is a dimensionless parameter, thus if multiplied by 100%, it gives the reflectance loss in percentage.

The mirrors used in this experiment to accumulate soiling naturally, were deployed in the structure shown in Fig. 1b, with one branch horizontal and the other tilted 45°. The only time they are removed from the structure, is when they are put in the TraCS frame for the measurements or for Scanning Electron Microscopy (SEM) analysis.

It should be noted that the left side of the mirrors (half) is uncoated, while the other half is coated (see Fig. 3). The mirrors were installed in the two positions previously referred to assess the anti-soiling coating performance dependency with the tilt angle. The measuring campaign started on May 2018 and lasted until September 2018. This period corresponds to the driest part of the year in the region of study, when most of CSP production would take place, along with very low precipitation levels, i.e. a mean average value around 36 mm/month, according to IPMA's (*Instituto Português do Mar e da Atmosfera*) records from 1971 to 2000, resulting in conditions prone to soiling deposition, and therefore the need for cleaning.

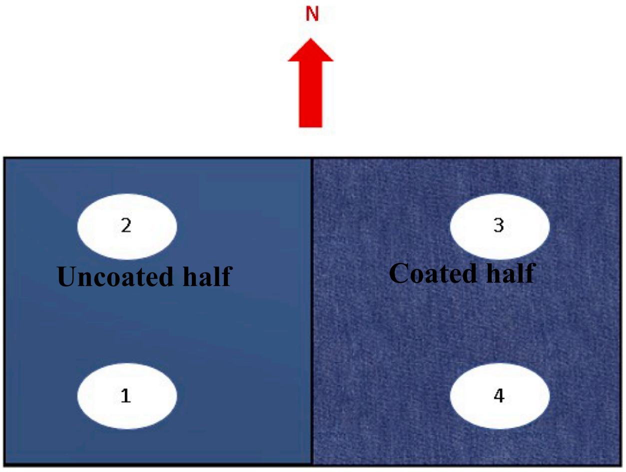


Fig. 3. Schematic representation of the measured areas in the mirror: the uncoated part of the sample is the left side (areas 1 and 2); the coated part is the right side (areas 3 and 4).

It should be noted that the coating does not affect significantly the mirrors transmissivity, since base reflectance values with cleaned mirrors showed a difference between coated and uncoated part of only 0.2 percentage points (Aranzabe et al., 2018).

It should be noted that the pyrheliometer has a full response area, defined by an acceptance half-angle of 1^0, which results in a circle with a diameter of 32 mm on the TraCS mirror surface considering the distance of 610 mm between the pyrheliometer's and the mirror plane. For more detailed information please consult (Bellmann, 2017).

Measurements of both mirrors' reflectance were performed considering four positions. These positions were kept the same throughout the experiment, for comparison reasons. A total of eight positions (four for each mirror) were analyzed, allowing a better characterization of the mirror's reflectance loss. The tilted mirror positions (1) and (4), are the ones on the lower side of the mirror, while (2) and (3) correspond to the upper part. The uncoated part of the sample is the left side and the coated part is the right side, respectively, as shown in Fig. 3.

3. Results and discussion

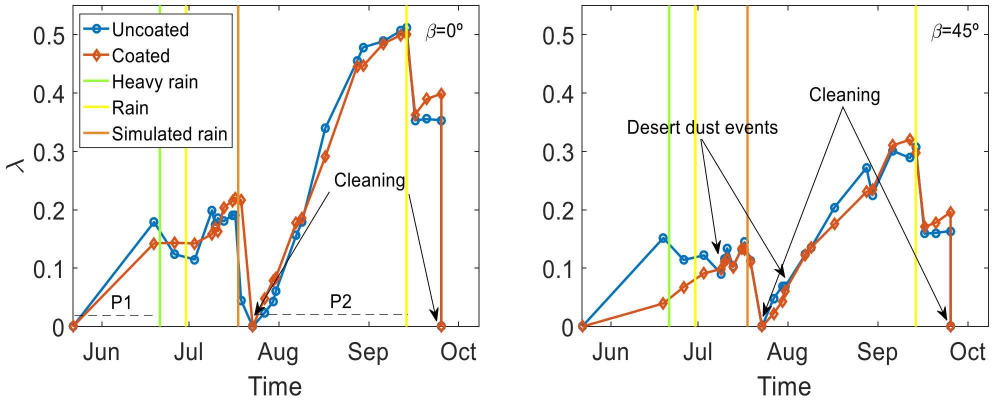
3.1. Experimental results

3.1.1. Soiling Index

The experiment lasted approximately 4 months, throughout the driest season of the year in the region of study. However, measurements of specular reflectance were only taken with clear-sky conditions and near solar noon to avoid lower DNI signal's magnitude and rapid oscillations, which can increase the measurement errors. In Fig. 4, the results obtained during the campaign are shown for the horizontal and tilted mirror samples. It should be noted that, in this figure, the results correspond to the mean value of the two measured positions for each half of the mirrors.

Variations in the results have been considered, since regular reflectance measurements on a standard mirror were performed, where a value of 0.0058 for relative standard deviation was obtained, corresponding to the experimental error associated with the measurements.

As observed in Fig. 4, in the initial days of the experiment, the coated samples (for both positions) are associated with lower Soiling Index values, with the coated part of the tilted mirror showing the lowest value, presenting a Soiling Index below 0.05 until the first occurrence of rain (see Fig. 4b). This highlights the good anti-soiling



(a) (b)

Fig. 4. Soiling index of the coated and uncoated parts of the mirror samples for: (a) β = 0°; b) β = 45°.

properties of the coated mirrors in the absence of cleaning compared to the uncoated, which reached a value around 0.15, three times higher than the coated one. The low Soiling Index for the coated tilted mirror means that particles' adhesion to the mirror is reduced due to the anti-soiling coating. This probably happens because of the photocatalytic effect, which degrades the organic particles, since between May and June there can still exist a significant concentration of atmospheric pollen. Regarding Fig. 4a, since the sample is horizontal, the Soiling Index is much higher than for the tilted sample (both coated and uncoated). This is explained by the fact that particles do not slip in the surface plane like they do for the tilted one.

From Fig. 4, it is also seen that the occurrences of rain have more impact in decreasing the overall value of Soiling Index in the uncoated mirrors than in the coated ones. However, more tests during the wet season need to be performed to assess its hydrophilic characteristic.

After the first cleaning procedure, for both coated and uncoated (horizontal position), the Soiling Index increased significantly, achieving a maximum value of almost 0.5 in mid-September. The obtained value is considerably high for the region of study (Ricardo Conceição et al., 2018a). From June to July some precipitation occurrences were observed, and consequently, the obtained Soiling Index was lower. From the end of July to mid-September, high temperature values and an absence of precipitation allowed particles to accumulate for a longer period, resulting in a very high Soiling Index for the considered region of study. Interestingly, until the precipitation event near mid-September, the Soiling Index increases drastically, resembling an exponential, meaning that particle accumulation is already saturating the mirrors' surface. Moreover, this indicates that the decreasing of specular reflectance with soiling overtime, usually linearly fitted for low soiling regimes, could be exponentially fitted for high soiling regimes using functions of the type $1 - \exp\left(-\frac{t}{\tau}\right)$, where t corresponds to time and τ to the characteristic time constant. Nevertheless, such topic is out of the scope of this work, where only linear fitting is used, as it will be shown next.

The Soiling Index during the dry period, for both coated and uncoated (horizontal position) is almost the same, since there is no precipitation, there is less dew in the summer, and most of the particles are mineral, not organic, which means that they cannot be decomposed by the photocatalytic effect. During these dry periods, it is probably a good idea to have a cleaning schedule, to make use of the hydrophilic characteristic of the coating.

It should be noted that for the tilted position (both coated and uncoated), a Soiling Index as high as for the horizontal sample (both coated and uncoated) was not achieved. This can be explained by the fact that particles will have a higher tendency to slip from the surface, as expected. Since it does not achieve a Soiling Index, as the one from the horizontal position, the surface is not yet saturated, and the data is reasonably well fitted by a linear function.

3.1.2. Soiling rates

Besides the Soiling Index, λ, the soiling effect variation over time, defined as Soiling rate, $\Delta\lambda$, is calculated and presented (see Table 1). The Soiling rate is calculated for two periods: the period from the beginning of the campaign until the first measurement made in mid-June, denoted P1; and the period between the first manual cleaning and the rain event near mid-September, denominated P2. Both these periods can be observed in Fig. 4a. The Soiling rates are calculated fitting the data linearly during the respective periods. Since P1 is only composed of two points, as seen in Fig. 4, the r^2 and *RMSE* are not included in Table 1, because they would be 1 and 0, respectively.

Table 1
Soiling rates (Δλ) per day for P1 and P2 and P2 coefficients.

	Δλ (P1)	Δλ (P2)	r^2 (P2)	*RMSE* (P2)
Uncoated β = 0°	0.006	0.011	0.96	0.05
Uncoated β = 45°	0.005	0.006	0.95	0.03
Coated β = 0°	0.005	0.010	0.97	0.03
Coated β = 45°	0.001	0.006	0.95	0.03

The results from Table 1 show that for the second period, P2, the soiling rates are much higher in comparison with the first one, P1. This means that the particle accumulation in the mirrors per day was more intense during the summer. The soiling rates found for P2, for both positions (horizontal and tilted) for the coated and uncoated parts of the mirrors are higher than the value of 0.004/day that was obtained in (Conceição et al., 2018a) for the same site. It can be observed that the soiling deposition over time increases during August relatively to June and July, mainly because the lack of precipitation occurrences. This factor allows for particles to accumulate onto the surfaces during a longer period, resulting in higher soiling related losses.

3.1.3. Soiling index intra-mirror variation

From the data analyzed in the box plot (see Fig. 5), the results for tilted mirror (coated and uncoated) are less prone to variations. However, for the horizontal sample (coated and uncoated), the values are higher and show larger dispersion.

Overall, the position (3) for the tilted mirror, which corresponds to the upper coated side of the sample, has the lowest soiling values. This may be because dew, sometimes, does not slip through the entire surface, instead stopping in the bottom of the sample, position (4), and particles are carried way from the top to the bottom where they accumulate.

3.2. Desert dust event

In the beginning of July (between 9 and 11), an occurrence of rain contaminated with dust from the Sahara Desert (Conceição et al., 2018) took place. The values show considerable dispersion and it is hard to evaluate the differences in optic behavior between coated and uncoated mirrors, mainly due to the non-uniform distribution of soiling. One of the phenomena that can cause this is the deposition of particles swept by rain contaminated with the Saharan Desert dust in agglomerates, meaning that certain areas of the mirrors have greater amounts of particles than others. For the tilted mirror a soiling rate of 0.015/day was achieved which is an unusual value for the PECS site (Conceição et al., 2018a). As consequence, it is difficult to have reliable measurements in both coated and uncoated mirrors. Still, this episode shows that the coatings tend to be inefficient in terms of contaminated rain, as water acts simultaneous as cleaner and dust carrier. Nevertheless, it would be very interesting to study the performance of this coating on, or near, a desert area to assess its endurance in harsh conditions.

During P2, the Barcelona Supercomputing Center (BSC) forecasts (Fig. 6) point out to an increasing dust load over the region of study, between 31st July and 7th August, which may be responsible for higher

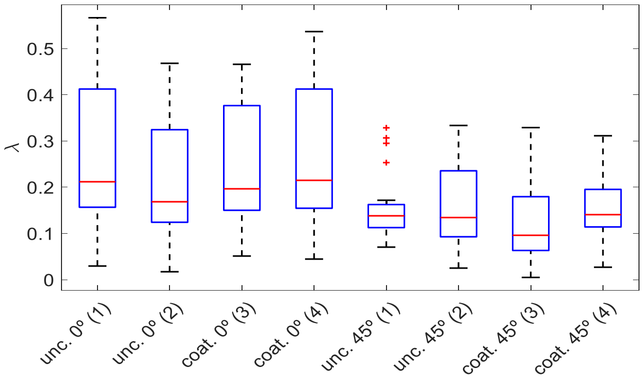


Fig. 5. Boxplot of all the Soiling Index (λ) results, with the respective location of the mirrors included within parenthesis.

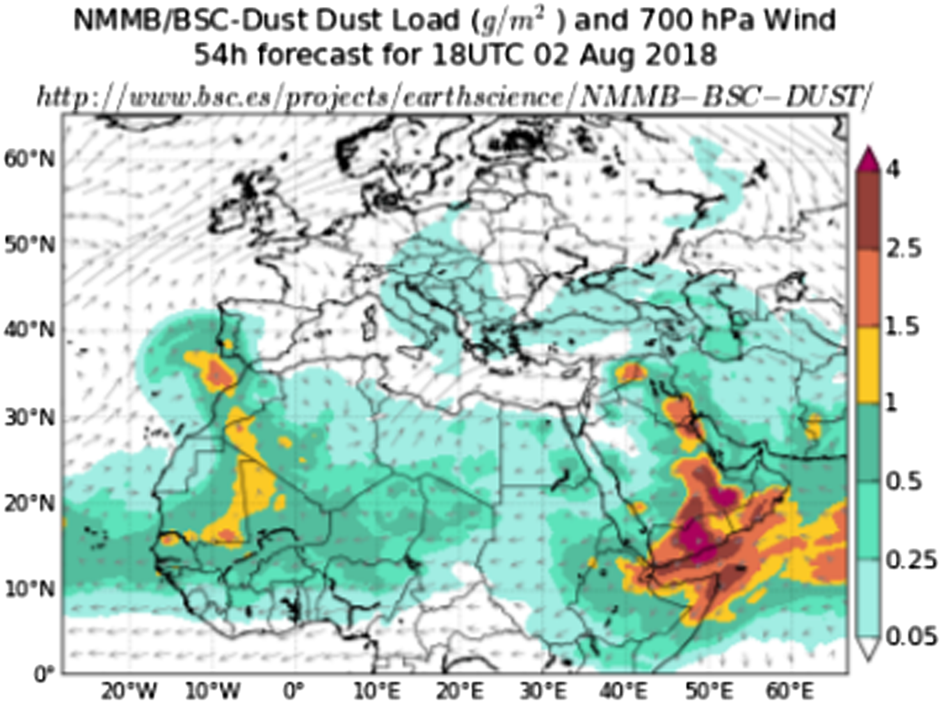


Fig. 6. BSC forecast dust load data for 2nd August 2018 (data and/or images from the (NMMB/BSC-Dust or BSC-DREAM8b) model, operated by the Barcelona Supercomputing Center. Available from: http://www.bsc.es/ess/bsc-dust-daily-forecast/.

particle deposition onto the surface of the mirrors, and therefore higher soiling rates. A value of 0.011/day was found for both coated and uncoated parts of the tilted mirror, while for the horizontal sample, this value was around 0.0135, being significantly high.

3.3. SEM analysis

To evaluate and quantify the amount and type of particles that adhere to the mirrors in this region during the measurement campaign, SEM analysis was performed. In Fig. 7, SEM images of certain areas in the different mirrors are shown. The images were taken from random places of each mirror, and it is assumed that these are representative of the whole surface. Two coated mirrors and two uncoated mirrors, smaller in size compared to the ones used on the TraCS system, were exposed outdoors in an identical structure as the one observed in Fig. 1b and installed near it. The mirrors were allowed to accumulate soiling under the same conditions as the ones used for measuring the Soiling Index. This procedure was carried out since smaller samples are the only ones that fit into the SEM chamber, contrarily to the ones used in the main experiment.

The obtained SEM images were taken in mid-September, from mirrors accumulating particles since mid-June. It is visible that the horizontal mirror presents higher number of particles in comparison with the tilted mirror. The black particles are organic material (carbon based), while the others correspond to mineral matter. In Table 2, it is shown the average area occupied by the organic particles (assuming they are circular) for each mirror. This analysis was made with ImageJ (https://imagej.net/Welcome), a free image analysis software. It should be noted that these values should be considered only as indicative, since there are errors associated with image analysis, and because it is assumed that the part of the mirror that was analyzed is representative of the whole surface, which might not be true, if the soiling is spread in a non-homogenously way.

From Table 2, the uncoated parts of the mirrors, for both positions, have the highest organic average particle area. For the horizontal mirror, the coated side has an average organic occupied area around 75% lower than the uncoated side, while for the tilted one, the coated parts shows a reduction of approximately 27%. The photocatalytic properties of the mirror may be the cause to this phenomenon, where the organic particles in the coated mirrors are being degraded.

3.4. Mirror performance and financial viability

To assess the effect of the anti-soiling coating in the mirrors' performance and energy cost-reduction at a plant scale, a cost impact analysis was performed. A study of the cost impact for a real case scenario was performed for an Andasol I type plant with A = 510 120 m^2 of solar field aperture area, 2136 $\mathrm{kWh/m^2}$/year ($E_{available}$ from typical meteorological year analysis) of solar resource and 16% solar-to-electricity efficiency (μ_{ele}) according to NREL (https://solarpaces.nrel.gov/andasol-1). A cost of 7c€/$\mathrm{kWh_{ele}}$ (C_{ele}) was assumed. The revenue for the coated, R^{coa}, and uncoated mirrors, R^{unc}, is roughly given by:

$$R^{coa} \cong (1-\lambda_{op}^{coa}) \times \mu_{ele} \times E_{available} \times C_{ele}, \tag{2}$$

$$R^{unc} \cong (1-\lambda_{op}^{unc}) \times \mu_{ele} \times E_{available} \times C_{ele}, \tag{3}$$

where $(1-\lambda_{op}^{unc})$ and $(1-\lambda_{op}^{coa})$ are the respective optical loss efficiency due to soiling, for both coated and uncoated mirrors. The difference between the two revenues can be described as the optical performance difference between the coated and uncoated mirrors:

$$\Delta R = R^{coa} - R^{unc} \cong (\lambda_{op}^{unc} - \lambda_{op}^{coa}) \times \mu_{ele} \times E_{available} \times C_{ele}. \tag{4}$$

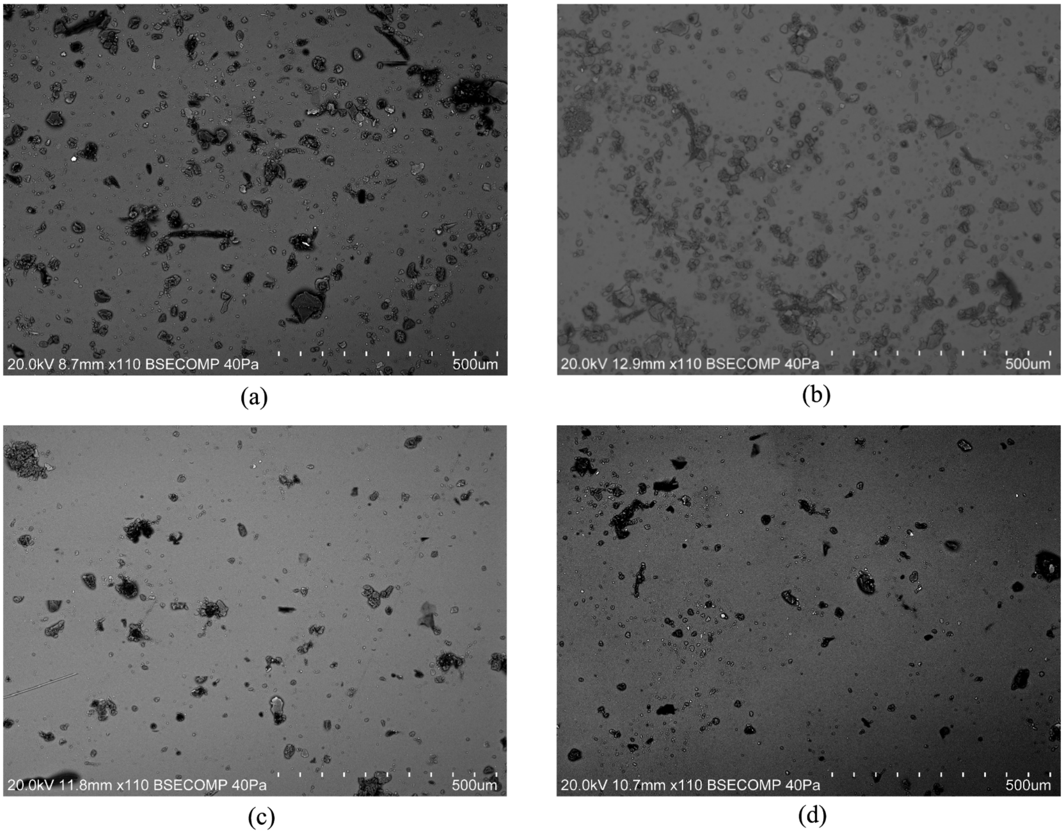
Considering the mean difference between the optical loss of coated and uncoated mirrors, as:

$$\bar{\delta\lambda} = \lambda_{op}^{\bar{u}nc} - \lambda_{op}^{\bar{c}oa}. \tag{5}$$

Eq. (6), which corresponds to Eq. (4) with the simplified term calculated in Eq. (5), shows the financial loss expected between uncoated and coated mirrors, defined by ΔP:

$$\Delta \mathrm{R} \cong \bar{\delta\lambda} \times \eta_{ele} \times E_{available} \times C_{ele}. \tag{6}$$

It is assumed that the mean optical losses are calculated from the



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

Fig. 7. SEM images of: (a) uncoated β = 0°; (b) coated β = 0°; (c) uncoated β = 45°; and (d) coated β = 45° mirrors (top left, top right, bottom left, bottom right, respectively).

Table 2
Average area of organic particles in the mirrors.

	Uncoated	Coated
β = 0°	346.3 μm^2	88.6 μm^2
β = 45°	401.6 μm^2	293.0 μm^2

mean values of the Soiling index of tilted coated and uncoated mirrors, determined during the experimental campaign, where a value of ~0.0113 was obtained. This value already contains the absolute reflectance difference between coated and uncoated mirrors referred before.

Substituting the values referred before in Eq. (6), an estimation of approximately 0.27 €/m^2/year of loss due to soiling was obtained. For a lifespan of 20 years, a total of 5.41 €/m^2 could be additionally invested in the anti-soiling coating to increase the revenue. Although, the product is not yet commercialized, a price much lower than the extra 5.41€/m^2 obtained, is expected from the manufacturers. During the lifespan of the power plant, a revenue of 2.8 M€ was calculated for the whole aperture area, which is the difference between using or not coated mirrors. In these estimations, it is assumed the same lifespan for the plant and the coating, since this is a simple economic analysis. Therefore, the value of 2.8 M€ and 5.41€/m^2 obtained using this approach, are to be considered as the maximum achievable, if the coating maintains its performance over the plant's lifespan. If a certain coating degradation factor overtime is assumed, which is not included in the calculations, these values will be lower. However, in a future work using a more extensive data set from a longer period, the coating degradation rate can be studied for a more realistic economic approach.

It should be noted that this is a simple economic analysis, however it allows to have initial evaluations that can be used by the industry or R&D institutions. These values and methodology can later be improved and deepened to achieve a more realistic and consolidated analysis.

4. Conclusions

The presented study includes a soiling measurement campaign performed during the driest season of the year in southern Europe, using coated and uncoated second-surface mirror samples. The main difference is seen between the end of spring and summer, when the photocatalytic effect of the coated samples is most effective at degrading organic particles present in the samples. This difference is also expected due to the lack of precipitation occurrences for this location during summer. The soiling ratio is more pronounced in the horizontal sample, since it is harder for particles to slip. Soiling rates for both coated and uncoated parts of the horizontal mirror have approximately the same value for period P1, around 0.005/day, which means the coating hydrophilic properties for the horizontal surface are not as evident. For the same period, but for the tilted sample, a decrease in soiling effect was detected for the coated side of the sample, which could be to the fact that both the photocatalytic and hydrophilic properties are working, and better performance can be obtained if the surface is tilted. For period P2, the lack of precipitation makes the hydrophilic characteristic effectiveness less pronounced, and at the same time, the number of organic particles is much lower than it was during spring, which also occults the photocatalytic effect, resulting in a soiling rate 0.006/day for the tilted sample (coated and uncoated part) and around 0.010/day for the horizontal one (coated and uncoated part).

Finally, a preliminary economic analysis was performed to assess the performance of the anti-soiling coating at a plant size scale, such as Andasol I, for a 20-year lifespan. It was observed that the use of this coating can lead to a revenue increase, with respect to the use of uncoated mirrors, of ~2.8 M€, which sets that the coated mirrors has a margin up to 5.41 €/m^2 of additional cost to the uncoated ones to be commercialized. The presented analysis, although simples, can be used as a reference for future market prices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adinoyi, M.J., Said, S.A.M., 2013. Effect of dust accumulation on the power outputs of solar photovoltaic modules. Renew. Energy 60, 633–636. https://doi.org/10.1016/j.renene.2013.06.014 Technical note.

Aranzabe, E., Azpitarte, I., Fernández-García, A., Argüelles-Arízcun, D., Pérez, G., Ubach, J., Sutter, F., 2018. Hydrophilic anti-soiling coating for improved efficiency of solar reflectors. AIP Conf. Proc. 2033. https://doi.org/10.1063/1.5067223.

Bellmann, P.M., 2017. Investigation of soiling on mirror and glass samples with regard to power losses in CSP and PV technologies. Technische Universität Dresden.

Boyle, L., Flinchpaugh, H., Hannigan, M.P., 2015. Natural soiling of photovoltaic cover plates and the impact on transmission. Renew. Energy 77, 166–173. https://doi.org/10.1016/j.renene.2014.12.006.

Cohen, G.E., Kearney, D.W., Kolb, G.J., 1999. Final report on the operation and maintenance improvement program for concentrating solar power plants. https://doi.org/10.2172/8378.

Cole, W.J., Frew, B.A., Gagnon, P.J., Richards, J., Sun, Y., Margolis, R.M., Woodhouse, M. A., 2017. SunShot 2030 for Photovoltaics (PV): Envisioning a Low-cost PV Future. https://doi.org/10.2172/1392206.

Conceição, Ricardo, Alami Merrouni, A., Lopes, D., Alae, A., Gonçalves Silva, H., Ghali Bennouna, E., Collares-Pereira, M., Ghennioui, A., 2018a. A comparative study of soiling on solar mirrors in Portugal and Morocco: Preliminary results for the dry season, in: SolarPACES. p. 220001. https://doi.org/10.1063/1.5117760.

Conceição, Ricardo, Silva, H.G., Collares-Pereira, M., 2018b. CSP mirror soiling characterization and modeling. Sol. Energy Mater. Sol. Cells 185, 233–239. https://doi.org/10.1016/j.solmat.2018.05.035.

Conceição, R., Silva, H.G., Fialho, L., Lopes, F.M., Collares-Pereira, M., 2019. PV system design with the effect of soiling on the optimum tilt angle. Renew. Energy. https://doi.org/10.1016/j.renene.2018.10.080.

Conceição, Ricardo, Silva, H.G., Mirão, J., Collares-Pereira, M., 2018c. Organic soiling: the role of pollen in PV module performance degradation. Energies 1–13. https://doi.org/10.3390/en11020294.

Conceição, R., Silva, H.G., Mirão, J., Gostein, M., Fialho, L., Narvarte, L., Collares-Pereira, M., 2018d. Saharan dust transport to Europe and its impact on photovoltaic performance: a case study of soiling in Portugal. Sol. Energy 160, 94–102. https://doi.org/10.1016/j.solener.2017.11.059.

Deffenbaugh, D.M., Green, S.T., Svedeman, S.J., 1986. The effect of dust accumulation on line-focus parabolic trough solar collector performance. Sol. Energy 36, 139–146. https://doi.org/10.1016/0038-092X(86)90118-0.

Ennaceri, H., Erfurt, D., Wang, L., Köhler, T., Taleb, A., Khaldoun, A., El Kenz, A., Benyoussef, A., Ennaoui, A., 2016. Deposition of multifunctional TiO2 and ZnO top-protective coatings for CSP application. Surf. Coatings Technol. 298, 103–113. https://doi.org/10.1016/j.surfcoat.2016.04.048.

Fernández-García, A., Álvarez-Rodrigo, L., Martínez-Arcos, L., Aguiar, R., Márquez-Payés, J.M., 2013. Study of different cleaning methods for solar reflectors used in CSP plants. Energy Procedia 49, 80–89. https://doi.org/10.1016/j.egypro.2014.03.009.

Kennedy, C.E., 2007. Advances in concentrating solar power collectors:mirror and solar selective coatings. Assoc. Ind. Met. Coaters Laminators (AIMCAL), Fall Techical Conf. 6103.

Lopes, F., Silva, H., Salgado, R., Cavaco, A., Canhoto, P., Collares-Pereira, M., 2018. Short-term forecasts of GHI and DNI for solar energy systems operation: assessment of the ECMWF integrated forecasting system in southern Portugal. Sol. Energy 170, 14–30. https://doi.org/10.1016/j.solener.2018.05.039.

Piedra, P.G., Llanza, L.R., Moosmüller, H., 2018. Optical losses of photovoltaic modules due to mineral dust deposition: Experimental measurements and theoretical modeling. Sol. Energy 164, 160–173. https://doi.org/10.1016/j.solener.2018.02.030.

Šúri, M., Remund, J., Cebecauer, T., Hoyer-klick, C., Dumortier, D., Huld, T., Stackhouse, P.W., Ineichen, P., 2009. Comparison of Direct Normal Irradiation Maps for Europe. SolarPaces 2009, 1–8.