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Water Saving in CSP Plants by a Novel Hydrophilic Anti-Soiling Coating for Solar Reflectors

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Abstract: In this work, results of the outdoor exposure campaign of a newly developed hydrophilic anti-soiling coating for concentrated solar thermal power (CSP) mirrors are presented. The material was exposed for nearly two years under realistic outdoor conditions and the influence of two different cleaning techniques was evaluated. Mirror samples were analyzed during exposure and their reflectance and cleanliness were measured. The performance of the anti-soiling coated mirror samples was compared to conventional uncoated silvered-glass mirrors. The coatings showed appropriate anti-soiling and easy-to-clean behavior, with a mean cleanliness gain of 1 pp and maximum values under strong soiling conditions of up to over 7 pp. Cleanliness of the coated samples stayed higher throughout the whole campaign before and after cleaning, resulting in lower soiling rate compared to the reference material. Taking into account these values and supposing a threshold for cleaning of 96%, the number of cleaning cycles could be decreased by up to 11%. Finally, the coated material showed negligible degradation, not exceeding the degradation detected for the reference material.

Keywords: concentrated solar thermal power; water saving; solar reflector; anti-soiling coating; outdoor test; reflectance measurement; soiling rate; cleaning method

1. Introduction

Concentrated solar thermal power (CSP) plants are integrated by large reflector surfaces that concentrate the direct normal irradiation (DNI) onto a receiver, where available solar energy is converted to useful thermal energy [1]. To avoid optical losses in the energy conversion process, it is crucial that the concentrating solar reflectors are kept as clean as possible, because soiling accumulated on them reduces their reflectance and consequently, the plants efficiency [2,3]. Cleaning the solar field implies high operation and maintenance (O&M) costs [4] and also creates an important issue in areas with water scarcity, which normally match with high DNI availability zones, where CSP plants are typically located. Consequently, a reduction of the soiling rate of the solar field and the cleaning needs, is one of the main challenges of this technology at present.

Among the different technical solutions implemented or under study in order to mitigate the soiling, special coatings deposited on the reflector's front surface (typically named as "anti-soiling", "self-cleaning" or "easy-to-clean" coatings) are becoming an attractive approach [5–7]. This technology is used in a variety of products nowadays, with glazing products being the foremost area of application [8].

Solar energy applications are also taking advantage of the efficiency increase over time, due to the soiling reduction in the optical surfaces through this kind of coatings [9], mainly in photovoltaic technology [10–12] but also more recently in CSP plants [13–15]. For CSP applications, anti-soiling coatings are applied both to the glass tubes of parabolic-trough collectors and to solar reflectors of all different concentrators. In this case, the advantage is expected not only with the increase of the plant's efficiency, but also in the reduction of the water consumption and O&M costs, thanks to having to carry out less cleaning activities.

IK4-Tekniker and Rioglass Solar are developing an innovative anti-soiling coating for concentrating solar reflectors [16,17]. In this case, the product is based on the hydrophilic effect, which consists on high surface energy and low contact angles between the surface and the water, in order to assure dirt particles' transportation off the surface. To be competitive, a proper anti-soiling coating for reflectors must meet following three requirements:

- Negligible reduction of the reflectance properties in the initial status.
- Appropriate durability over time, which means that the coating must keep its optical properties after being exposed to the weather agents (abrasion, temperature, humidity, pollutants and radiation).
- Appropriate behavior in reducing the dust accumulation on the reflector surface under real outdoor conditions.

While the first two features of the anti-soiling coating developed by IK4-Tekniker and Rioglass Solar were addressed in [18], this paper is focused on studying the behavior of the coating with regard to the last requirements, presenting the results of a long-term outdoor test campaign performed by DLR and CIEMAT at the Plataforma Solar de Almería (PSA).

2. Materials and Methods

This section describes the anti-soiling coating material analyzed in this work, the different cleaning methods used to wash the samples, the equipment used over the test campaign, the measurement frequency and the optical parameters studied.

Six 4 mm silvered-glass reflector samples with dimensions of 20 cm × 40 cm, developed by IK4-Tekniker and Rioglass, were installed at the PSA from 25 October, 2017 until 31 August, 2019 comprising a period of nearly two years. These samples are divided into two parts, one of which is covered with a hydrophilic anti-soiling coating while the other one does not have the coating layer. The reflectors were exposed on two metallic racks with a tilt of 45 degrees in south direction (see Figure 1).

Figure 1. Exposure racks with mirror samples installed in south direction at the Plataforma Solar de Almería (PSA) facilities.

Two different cleaning methods were applied, demineralized pressurized water and a wet brush. For the former, a pressure washer model HDS 10/20-4M manufactured by Kärcher (Winnenden, Germany) was utilized to clean the mirrors situated on the structure S1. The cleaning operations were performed at ambient temperature and 100 bar pressure. In addition, the distance between water pressure nozzle (aperture angle 25°, diameter 0.54 mm) and the samples was kept constant at 50 cm for all the samples. For the latter, a soft brush made with horse tail hair in combination with flowing water was employed as cleaning method for the 2nd structure S2. For both methods, 5 sweeps were done to wash the samples. In order to avoid differences in the methodology, the reflectors were always cleaned by the same operator and in the same conditions. Then, a suitable comparison and evaluation of the cleaning methods can be performed for this anti-soiling treatment. In addition to the regular cleaning, two special cleanings were performed. These resets just comprised the exhaustive cleaning with the brush technique until all soiling was removed from the samples on all structures. The first reset was performed after 8 months and the second after 20 months of exposure. After completing the exposure campaign, the samples returned to the laboratory and their reflectance was measured after abundant cleaning with soft paper tissue and demineralized water.

The optical characterization device used for this study was the 115R-USB reflectometer manufactured by Devices and Services Co. (D&S, Dallas, TX, USA) [19]. This instrument is able to measure the specular reflectance $\rho_{\lambda,\phi}(\lambda,\theta_i,\phi)$, at a the wavelength of λ = 660 nm, an incidence angle of θ_i = 15° and an acceptance angle of ϕ = 12.5 mrad. Furthermore, varying the position of the support screws, it is possible to adapt the height of the reflectometer to the mirror curvature and to adjust the beam path to obtain a correct measurement. In addition, the D&S is lightweight, portable and the influence of diffuse light is negligible, thus, it is appropriate for outdoor measurements. Three measurements were taken on the coated and non-coated surface with a mask to measure always in the same point, where coated part is on the left side and uncoated part is on the right side (see Figure 1). The measurements were taken according to the current version of the SolarPACES Reflectance Guideline [20].

Regarding the measurement frequency, both structures were measured before cleaning every 2 weeks. Structure 1 as well as structure 2 were then washed and measured after cleaning every 2 weeks.

From the reflectance measurements, several meaningful parameters were determined to evaluate the coating. The cleanliness factor, ξ, is defined as the ratio of the actual reflectance, $\rho_{s,\phi}$, to the initial value in the perfectly clean state, $\rho_{s,\phi,clean}$:

$$\xi = \frac{\rho_{s,\phi}}{\rho_{s,\phi,\text{clean}}} \tag{1}$$

During the campaign, the cleanliness value may be influenced by degradation. The cleanliness value equals 1 at the beginning of the campaign after abundant cleaning in the laboratory with demineralized water and soft paper tissues, followed by removal of remaining particles with pressurized air, to assure maximum reflectance. While the samples stay outside during exposure, the cleaning is usually not able to completely remove all the soiling completely and the reflectance in the perfectly clean state is unknown. If degradation decreases the reflectance in addition to the soiling, this will directly influence the cleanliness parameter.

One important parameter derived from the cleanliness, is the difference between the cleanliness of the coated anti-soiling samples, ξ_{AS}, and the uncoated reference material, $\xi_{uncoated}$, in the following referred to as cleanliness gain, Δ_ξ:

$$\Delta_\xi = \xi_{\text{AS}} - \xi_{\text{uncoated}} \tag{2}$$

In the case that this parameter is positive, the cleanliness of the anti-soiling material is higher than for the uncoated reference material, which means there is an advantage of the anti-soiling coating. Negative Δ_ξ values show a disadvantageous behavior of the coating compared to the reference material.

The accumulated cleanliness gain, $\overline{\Delta_\xi}(t)$, after exposure at a certain exposure time, t, can be calculated by integrating the reflectance difference over the analyzed exposure time dividing by the exposure duration Δt:

$$\overline{\Delta_\xi}(t) = \frac{\int_{t=0}^{t} \Delta_\xi \, \mathrm{d}t}{\Delta t} \tag{3}$$

It represents the mean cleanliness difference, taking into account the varying measurement frequency throughout the campaign. The accumulated cleanliness gain determines the actual advantage of the respective coating compared to the reference material until the analyzed point in time. For the calculation of this value, a linear behavior of the cleanliness between two measurements is assumed.

Finally, one further parameter can be determined supposing this linear behavior, the soiling rate $\hat{\xi}$. The soiling rate is just the change of cleanliness over time and it is usually expressed in pp/day. Within this investigation it is calculated taking the actual cleanliness value before cleaning subtracting the value after cleaning from the last measurement, divided by the time interval between the measurements Δt_c.

$$\hat{\xi}(t) = \frac{\xi_{\text{before}}(t) - \xi_{\text{after}}(t - \Delta t_c)}{\Delta t_c} \tag{4}$$

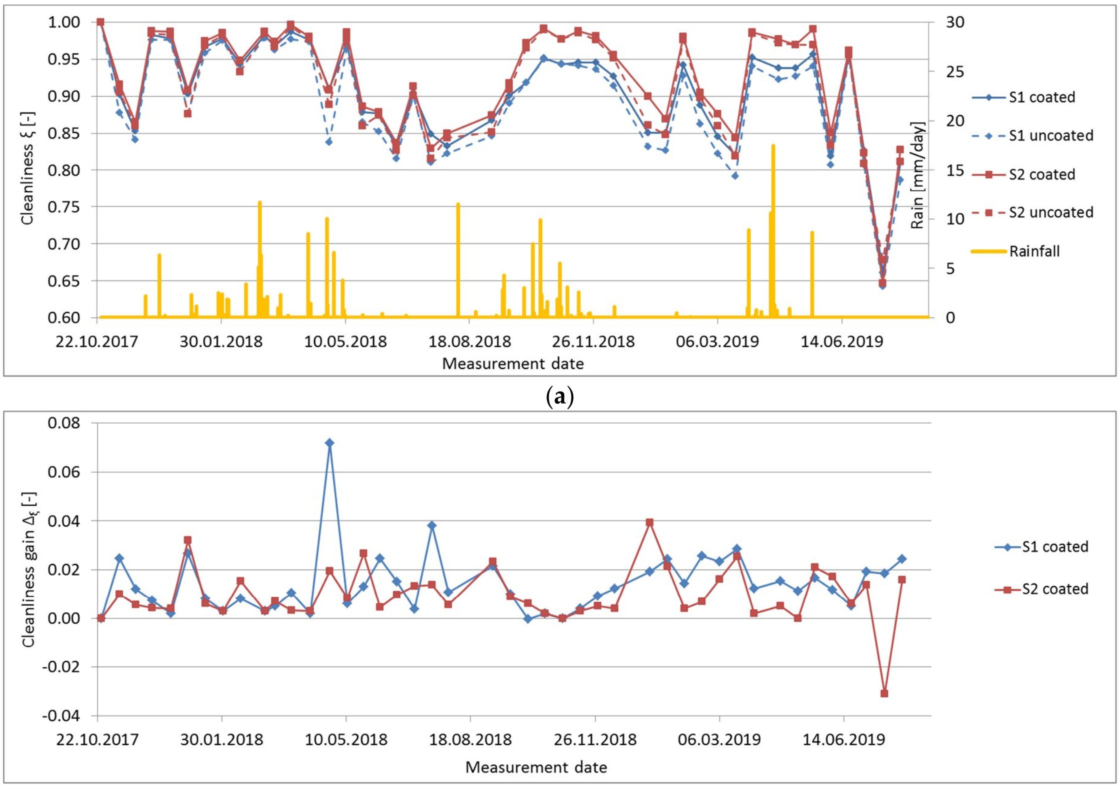
3. Results

As the whole outdoor exposure campaign produced a lot of data, these are separated into several groups. Data are separated between the values before cleaning, which means in the soiled state, and the values after cleaning.

In Figure 2 the data for S1 and S2 before cleaning is displayed. Two graphs are included, the first showing the cleanliness factor of the different materials, ξ, together with the amount of daily rain (in mm/day). The second shows the cleanliness gain of the coatings compared to the uncoated material, Δ_ξ.

The following observations can be made from the analysis of these graphs:

- The overall cleanliness factor of samples for S2 is higher than for S1. This is due to the fact that the cleaning with brush is more effective and able to restore the cleanliness basically to its initial values. This fact will be confirmed by the values in the clean state in the following section.
- The cleanliness is higher in periods with a high quantity of rain. Rain usually acts as a natural cleaning mechanism and prevents the samples from excessive soiling.
- The cleanliness gain of the coated samples for both structures is higher when the soiling is stronger and thus the overall cleanliness is lower. The stronger the soiling is, the better the coatings can fulfill their purpose of avoiding the soiling (this can be extracted from the combinations of both graphs).
- The cleanliness gain remains positive for the whole exposure campaign, proving a positive effect of the coatings for all occurring soiling situations. There is only one single event where the coating shows a negative value for S2. This was an event of exceptionally strong soiling due to light rain in combination with a dusty atmosphere (mean cleanliness of 0.66). These events lead to a very inhomogeneous soiling pattern on the samples (Figure 3) and to a high standard deviation of the measurements. With these high deviations, the probability of the occurrence of aberrations is increased. The rain event in this case was too weak to contribute a sufficient quantity to be detected by the rain gauge measurements.
- The highest cleanliness gain Δ_ξ detected was as high as 7.2 pp for S2 after another medium to strong soiling event (mean cleanliness 0.88 on that day).
- The mean cleanliness gain before cleaning is 1.4 pp for S1 and 0.9 pp for S2. When only situations of stronger soiling are evaluated, the mean cleanliness gain is even higher. Looking only at events with a high soiling level (cleanliness below 0.9), the mean cleanliness gain rises up to 2.4 pp (S1) and 1.5 pp (S2).



(**a**)

(**b**)

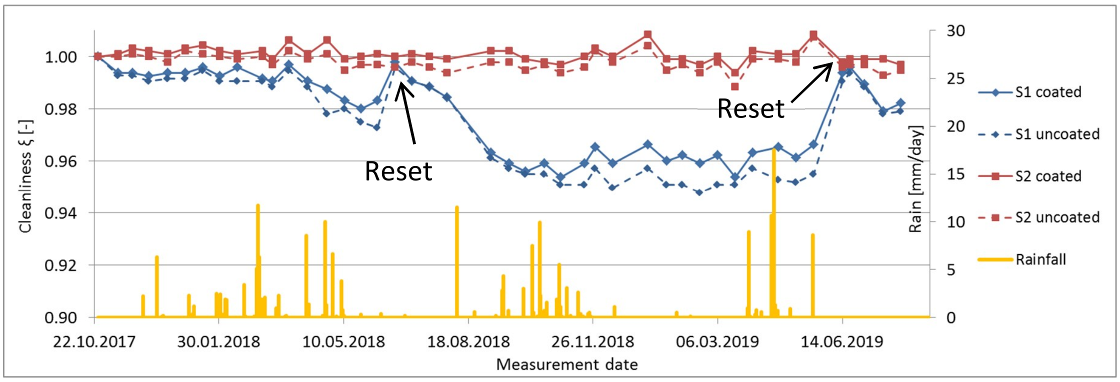
Figure 2. Data before cleaning, (**a**): cleanliness factor, (**b**): cleanliness gain.

Figure 3. Sample surface after a strong soiling event, showing an inhomogeneous soiling pattern.

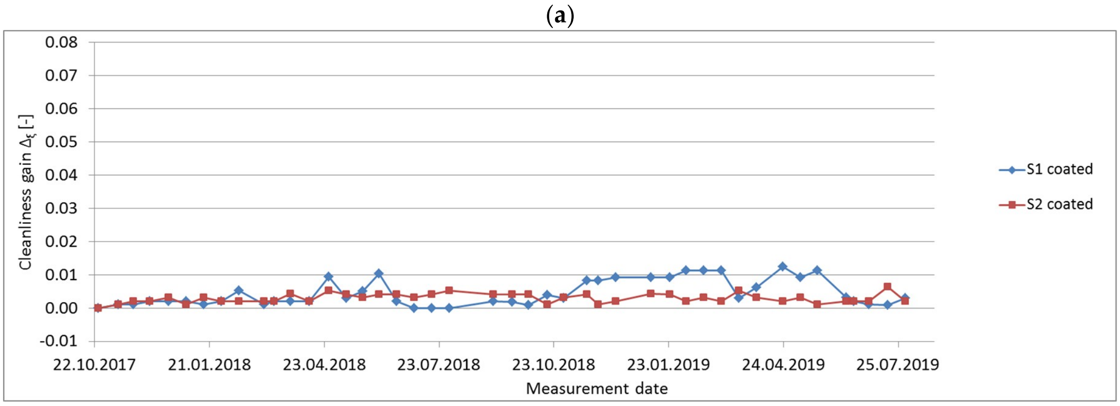
In Figure 4 the data for the values after cleaning is presented, in the same way as in Figure 2 for the before cleaning values. This representation is especially useful to analyze the "easy-to-clean" properties of the coatings as well as the cleaning procedures themselves. Observations that can be drawn from these graphs are the following:

- The cleanliness after cleaning remains higher for S2 during the whole exposure campaign and always reaches values around 1. The values even reach values slightly higher than 1 due to the measurement uncertainty of the reflectometer. Therefore, the cleaning method using the brush is much more effective than the high pressure water method.

- The cleaning method with pressurized water is not able to restore the initial cleanliness values over the whole exposure campaign ($\xi < 1$). Remaining soiling stays on sample surfaces decreasing the reflectance of the samples on S1. The effect is cumulative, showing decreasing values after cleaning in certain periods, especially after the first reset when strong soiling appears (compare Figure 2). This tendency is more pronounced for the uncoated reference material. That also influences the before cleaning values in Figure 2, where the difference between S1 and S2 is especially strong in periods of lower soiling after the accumulation of soiling on S1.
- After the two resets (extensive cleaning, marked in the chart of the cleanliness factor), the initial cleanliness is also nearly restored for S1, indicating negligible degradation.
- The cleanliness gain Δ_ξ after cleaning is lower than before cleaning. This underlines the fact that Δ_ξ is more pronounced with stronger soiling. Nevertheless, it stays in the positive regime for the whole campaign and thus proves the advantage of the anti-soiling coatings and indicates the positive effect on the "easy-to-clean" property.
- The mean cleanliness gain is also higher for S2 because of the lower cleanliness of S1.



(**a**)



(**b**)

Figure 4. Data after cleaning, (**a**): cleanliness factor, (**b**): cleanliness gain.

To evaluate if degradation affected the samples during outdoor exposure, their reflectance was measured in the laboratory before and after the exposure. In Table 1 the initial and final ξ values are displayed together with the resulting cleanliness loss, $\Delta\xi$. The measured losses do not exceed 0.004 in any of the cases, which is still within the uncertainty of the reflectometer. This leads to the conclusion that no perceivable degradation affects the materials within the tested duration.

Table 1. Reflectance measurements performed in the laboratory before and after exposure together with the reflectance loss.

Material		Initial ξ [–]	Final ξ [–]	Cleanliness Loss Due to Degradation, Δξ [–]
S1	Coated	1.000	0.997 ± 0.006	−0.003 ± 0.006
	Uncoated	1.000	0.996 ± 0.003	−0.004 ± 0.003
S2	Coated	1.000	1.001 ± 0.003	0.001 ± 0.005
	Uncoated	1.000	0.999 ± 0.002	−0.001 ± 0.004

In Figure 5 the accumulated cleanliness gain, $\overline{\Delta_{\xi}}(t)$, is displayed. In the beginning fluctuations of the values are stronger, because the overall duration is lower. The values become more stable with longer exposure. $\overline{\Delta_{\xi}}(t)$ remains higher for S1 for the whole exposure period. The final values of the curves after 22 months of exposure also represent the overall accumulated cleanliness gain of the coatings regarding the whole campaign. These values are $\overline{\Delta_{\xi,S1}}$ (22 months) = 1.0 pp and $\overline{\Delta_{\xi,S2}}$ (22 months) = 0.7 pp for the two structures. The better behavior of the coated samples exposed in the structure S1 is due to the higher soiling level of these samples during the outdoor exposure, as a consequence of the lower efficiency of the cleaning method applied. This fact indicates that the anti-soiling coating developed will show a better behavior in areas with higher soiling rates, such as the arid zones where the CSP plants are installed.

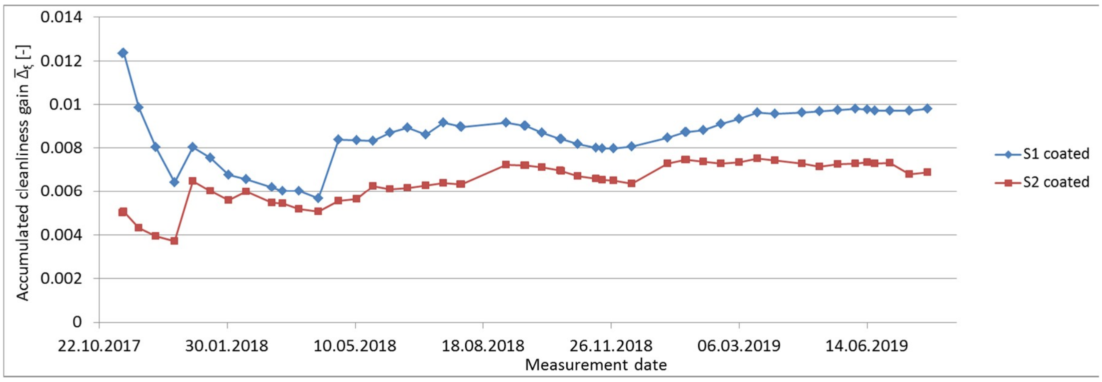


Figure 5. Accumulated cleanliness gain for both structures.

The development of the soiling rate over the exposure period is displayed in Figure 6. The values are always negative as they present a loss in cleanliness over time. Higher soiling rates can be appreciated for the uncoated material. As already seen in the graphs for the cleanliness factor before cleaning, soiling rates are lower for rainy periods. Soiling rates reach values of up to 2.3 pp/day in cases of strong soiling.

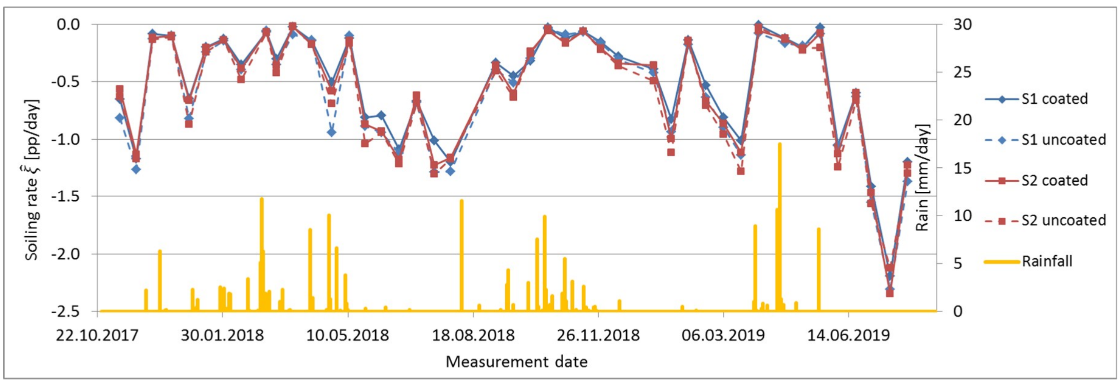


Figure 6. Soiling rate for both materials and structures.

In Table 2 the mean soiling rates are displayed for coated and uncoated samples on both structures. The soiling rate for the coated material is lower than for the uncoated material (average of both structures is 0.54 instead of 0.60 pp/day), once again proving the positive effect of the anti-soiling coating.

Table 2. Mean soiling rate, time until cleaning and number of cleanings per year.

Material	S1 Coated	S1 Uncoated	S2 Coated	S2 Uncoated
Average soiling rate [pp/day]	−0.52	−0.59	−0.56	−0.60
Time until cleaning [days]	7.72	6.81	7.16	6.63
Number of cleanings per year	47.34	53.63	50.99	55.06

The Wascop project, during which this current study has been conducted, is focused on the water saving potential of different technologies. One possibility to reduce water consumption by the use of anti-soiling coatings is to decrease the cleaning frequency. To calculate the benefit of the coating, a fixed cleanliness threshold of $\xi = 0.96$ is assumed, below which cleaning is performed. Taking into account the mean soiling rates presented above, the duration when this value is reached can be calculated. The number of days until cleaning is as well given in Table 2. The longer intervals between cleaning events would therefore result in 6.3 performed events less per year for S1, and respectively 4.1 events less for S2, when using the anti-soiling coating. This is a reduction of the number of performed cleanings of 11.7% and 7.4% respectively. It is important to highlight that this calculation has been performed for a specific site and under several assumptions, such as a constant soiling rate, a constant cleaning frequency every two weeks and a fixed cleanliness threshold of 0.96. Therefore, the results obtained are only illustrative.

4. Conclusions

The results of the herein presented outdoor exposure campaign of a novel anti-soiling coating for silvered-glass solar reflectors, shows the benefit of the application of these coatings compared to state-of-the-art commercial silvered-glass mirrors. The main benefits of the coating are the following:

- The anti-soiling effect of the applied coatings leads to a higher cleanliness of the reflectors throughout the exposure campaign. Taking into account the whole campaign, an accumulated cleanliness gain of 1.0 and 0.7 pp is reached, for pressurized water and brush cleaning respectively. When only the samples in the soiled state (before cleaning) are evaluated, the accumulated cleanliness gain increases to 1.4 and 0.9 pp, respectively. These values are even higher for situations of stronger soiling: for a cleanliness below 90%, the accumulated cleanliness gain increases to 2.4 and 1.5 pp respectively. The detected maximum momentary cleanliness gain reaches over 7 pp for a single soiling event.
- Lower soiling rates are detected for the anti-soiling coated samples, with a minimum value of 0.52 pp/day for the coated samples on S1, and a maximum of 0.60 pp/day for the uncoated samples on S2.
- The "easy-to-clean" properties of the anti-soiling coatings facilitate the cleaning process and thus help to recover the initial cleanliness of the reflectors.
- Fewer cleaning cycles have to be performed for the coated mirrors to reach the same mean cleanliness compared to uncoated mirrors. For a constant threshold cleanliness of 0.96, the number of cleaning cycles in Tabernas, Spain can be reduced by 7% to 12% for brush cleaning and pressurized water, respectively, considering a constant soiling rate and a fixed cleaning frequency of 2 weeks.
- The coatings show excellent durability during the course of the whole campaign and showing no signs of degradation.

- The investigated site represents an environment with relatively little dust in the atmosphere, leading to low soiling rates. The performance of the coatings is expected to be better for high soiling sites because the coating has demonstrated a higher effectiveness with stronger soiling.

The investigated coatings are still in the development phase. For a final evaluation, the commercial viability of the application of the coatings has to be studied before implementation. The result of this study will be basically the balance of the additional cost of the coating application and the expected benefit for the plant operation. The cost of the coating will mainly depend on the size of the solar field and the type of reflector to be installed. The benefit of the coatings is a complex subject which depends on many factors, among others plant design and operation (size of solar field and storage, technology used, operational strategy, cleaning technique) as well as the location (environmental conditions, soiling development, water availability).

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