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Comparative study of soiling effect on CSP and PV technologies under semi-arid climate in Morocco

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ABSTRACT

Soiling of solar collectors reduces the efficiency of both concentrating solar power (CSP) and photovoltaic technologies (PV), and increases the operations and maintenance (O&M) costs. Many countries with significant solar potential such as Morocco are located in regions characterized by dry and harsh climatic conditions, dust storms and high pollution. This study investigates the impact of soiling on PV and CSP technologies under a semi-arid climate in BenGuerir city of Morocco. For this purpose, one year of data collected from two types of soiling sensors, a Tracking Cleanliness Sensor (TraCS) and DustIQ, was evaluated. A meteorological station installed at Green Energy Park (Morocco). A period with red rain events and a dry period were selected to quantify the impact of soiling on both technologies during these periods. It is found that the soiling effect for CSP mirrors with an annually averaged soiling rate of -1.18%/day is around 5 to 6 times higher than for PV (-0.23%/day). The loss due to soiling during red rain events has been observed more pronounced compared to the dry period.

1. Introduction

Energy is a crucial factor for the development of countries, especially with the industrial evolution and the rapid increase in energy demand. To accompany this development, Morocco launched a solar plan where solar energy production shall reach 80 GW by 2032 [1]. To achieve this goal, several solar plants have been built, e.g., the parabolic trough power plant Noor I and Noor II, with a capacity of 160 MW and 200 MW, respectively. Noor III is a solar power tower plant with a capacity of 150 MW, and Noor IV PV plant of 70 MW [2]. The selected locations for these projects are not only characterized by a very high solar potential, but are also subject to high dust aerosols loads due to the pronounced harsh climate conditions [3]. Therefore, soiling of solar collectors remains a major factor in yield loss, thus affecting the production and increasing O&M costs [4]. Soiling information improves the yield prediction for project development [5–7], and can help to optimize the solar plant's economic yield by optimizing the cleaning schedule [8–13]. The optical effect of soiling has been broadly investigated for photovoltaic (PV) [14–17], and fewer works exist regarding this effect on concentrating solar power (CSP) [7,13,18–20]. Reviews of soiling research provide insights into the findings of these studies [21–26]. They have concluded that the accumulation of dust on the surface of PV panels and CSP mirror surfaces is one of the most significant factors leading to a decrease in the optical efficiency of the solar collectors and consequently to a lower yield of the solar installations, especially in arid and semi-arid climates. The typical exposure of transparent glass and mirrors methodology was mostly used to quantify the impact of soiling on CSP and PV technologies. However, this method is not entirely effective for assessing soiling in real solar projects, as the frequency of measurements can be weeks or even months. The measurement procedure of exposed samples can influence the results, as it may be necessary to move the samples to a laboratory in order to perform the measurements, which increases the uncertainty of the results. Recently, new commercialized real-time optical soiling sensors have begun to be used in soiling assessment studies for PV technology, like MARS^{TM}, Atonometrics [27] and DustIQ, Kipp&Zonen [28], and also for CSP technology, such as Tracking Cleanliness Sensor (TraCS) from Germany aerospace center (DLR) [29] and Fraunhofer's AVUS sensor. Moreover, recent developments in the field of optical soiling sensors are reported in the literature [30–32]. DUSST is one of the promising optical sensors that shows good performance in quantifying PV soiling loss [32–34]. However, this sensor still needs to be improved [35]. These sensors may be the future of standardization of soiling effect measurements, as they provide many advantages and allow for easier and reliable soiling measurement [36,37].

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Nomenclature

Greek symbols

ΔSR	The daily Soiling Rate
ρ_0	Reference reflectance of the mirror (at each last cleaning) (%)
SR	The daily Soiling Ratio
SR_1	Soiling Ratio measured by the sensor 1 of the DustIQ
SR_2	Soiling Ratio measured by the sensor 2 of the DustIQ
SR_d	The daily Soiling Ratio of the current day
SR_{d+1}	The daily Soiling Ratio of the following day

Abbreviations

AOD	Aerosol Optical Depth
AOI	Sun's Angle Of Incidence
BSC	Barcelona Super Computer
CSP	Concentrated Solar Power
GEP	Green Energy Park
LFC	Linear Fresnel Collector
O&M	Operation and Maintenance
PV	Photovoltaic
PvSM	Photovoltaic Soiling Monitor
TraCS	Tracking Cleanliness Sensor

The effect of soiling on PV and CSP solar collectors has been discussed independently in the literature, but only few studies such as Bellmann et al. [38] compare simultaneously the impact of soiling on the two technologies under the same conditions. They found a factor of 8 to 14 between CSP and PV soiling rates for the same particle surface density in solar glass and mirror samples exposed in southern Portugal. The continuously recorded cleanliness data from the tracking cleanliness sensor (TraCS) and a photovoltaic soiling monitor (PVSM) showed that the soiling rate is 8 to 9 times higher for the TraCS mirror sample compared to PVSM. Azouzoute et al. [39] have evaluated the optical impact of soiling on both the PV and CSP technologies by measuring the loss in reflectance and transmittance for mirror and glass samples respectively, exposed to outdoor natural dust accumulation during the dry period of the year in Morocco. This study concluded that the loss due to soiling reaches up to 12% for PV glass samples, while optical properties of CSP mirrors are three times more affected by soiling than PV glass samples. However, the low factor between CSP and PV here stems from the long time without cleaning and then occurring the saturation effect of soiling.

Nowadays, with the great interest in hybrid PV and CSP solar power plants [40–42], the simultaneous assessment of the soiling effect on CSP and PV technologies becomes necessary to provide additional guidance for a more accurate evaluation and efficient implementation of this type of solar projects. Moreover, many industries are ready to adopt solar energy as a primary energy source [3], using CSP as a cost-effective thermal energy storage technology [42,43], or as a source of heat needed in some industrial thermal processes (commonly referred to as SHIP: Solar Heat for Industrial Processes) [44,45], combined with PV to meet electrical energy needs. For this purpose, a long-term comparative analysis that addresses the effect of soiling on the efficiency of CSP and PV solar collectors in a semi-arid climate was carried out, and the results are presented in this work. Two real-time soiling monitoring sensors for the two technologies have been exposed for a period of one year at the Green Energy Park research facility, to quantify the impact of soiling during the entire year. This provides an idea of the soiling effects in the region and similar climates, which can be considered for the design of the optimal cleaning strategy for CSP, PV or hybrid solar plants.

This work is structured as follows: Section 2 describes the methodology used to measure soiling for both CSP and PV technologies. Further, the data processing procedure as well as the sensors used to measure the meteorological parameters of the studied site are described. Section 3 shows the results and discussion including the soiling campaign results and a comparison of daily soiling rate values of both CSP and PV technologies. A red rain event and the impact of dust storms on the optical efficiency of solar collectors is discussed. Section 4 highlights some soiling mitigation solutions. In Section 5, a conclusion of the results is given.

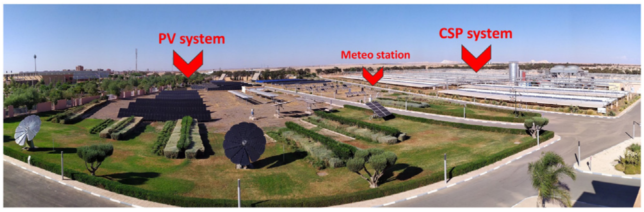

Fig. 1. Green Energy Park research facility in BenGuerir.

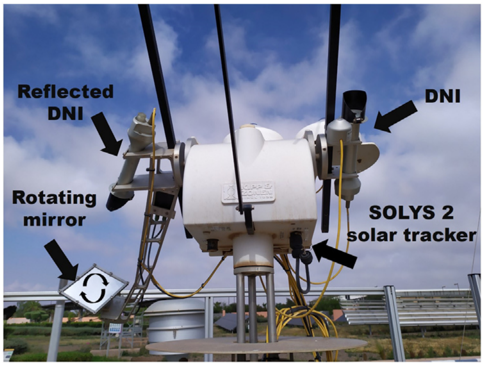

Fig. 2. Tracking cleanliness sensor (TraCS) installed at Green Energy Park, Morocco.

2. Soiling and Meteorological Measurements Data Set

To investigate the effect of soiling on CSP and PV technologies, two soiling sensors were installed at the Green Energy Park research facility (Fig. 1) in BenGuerir, Morocco (Latitude: 32.22 °, Longitude: -7.92 °). The sensors are exposed to outdoor soiling accumulation from March 1^{st}, 2018 to March 1^{st}, 2019 to continuously quantify the soiling effect on CSP and PV collectors. A meteorological station was installed as well to measure the environmental conditions on the site.

2.1. CSP Mirror Soiling Measurements

The soiling measurement for CSP technology was performed using the tracking cleanliness sensor (TraCS) [29], installed on a SOLYS 2 double axis solar tracker from Kipp & Zonen. The TraCS is based on two pyrheliometers. The first one measures the direct normal irradiance (DNI) coming directly from the sun. The second measures direct normal irradiance reflected from a CSP mirror sample (DNI_{ref}) that is also attached to the solar tracker and to a rotating holder to extend the measurement area (Fig. 2). The pyrheliometers are cleaned on a daily basis to ensure the accuracy of DNI and DNI_{ref} measurements. While the mirror sample was left without cleaning to accumulate soiling, resulting in a decrease in DNI_{ref} due to soiling. Therefore, the impact of soiling on the reflectance of the mirror sample can be derived by comparing the two pyrheliometer signals.

The daily soiling ratio (SR) is defined as the average value over the day of the normalized ratio between the reflected direct normal irradiance, DNI_{ref} of the mirror and the measured direct normal irradiance DNI. Note that the data is measured with one-minute temporal resolution and only the data points with $DNI \geq 500\ W/m^2$ are averaged, to

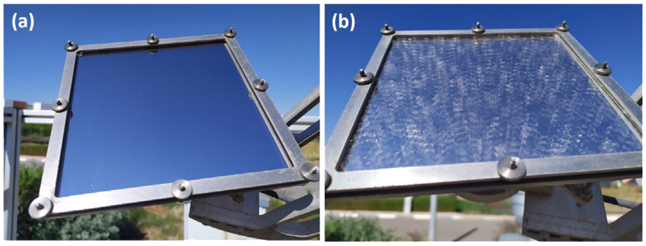

Fig. 3. Clean mirror sample; (b). Mirror sample after two weeks of exposition of the TraCS system at Green Energy Park, Morocco.

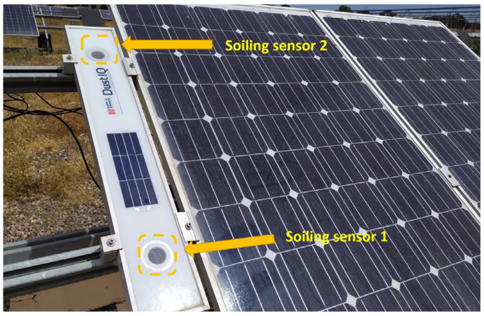

Fig. 4. DustIQ installed at Green Energy Park, Morocco.

avoid data fluctuations caused by the low DNI measurements.

$$SR = \frac{1}{N}\sum_{i=1}^{N}\frac{\rho_i}{\rho_0} \tag{1}$$

N is the number of the daily selected data points and ρ_i is the measured reflectance at each selected data point, given by:

$$\rho_i = \frac{DNI_{ref}}{DNI} \tag{2}$$

ρ_0 is the reference value of the reflectance recorded during each last cleaning. This reference value must be taken into account to avoid the effect of improper cleaning and small changes in the mirror alignment, which can influence the irradiance that reaches the pyrheliometer.

In this study, the temporal changes of the SR values are more important than the absolute ones, since the soiling ratio of the following day SR_{d+1} will be compared to that of the current day SR_d to calculate the daily soiling rate ΔSR_d (Eq. 3).

$$\Delta SR_d = (SR_{d+1} - SR_d) * 100\ [\%/day] \tag{3}$$

ΔSR is the daily change by which efficiency is reduced due to soiling accumulation or increased due to cleaning [4], for instance, a daily reduction in SR from 0.95 to 0.92 represents a ΔSR of -3%/day of optical loss due to soiling. This parameter is usually used for a better comparison of the soiling between different sites or different solar technologies [13,46]. If it is positive, it means that the collector surface become cleaner, and if it is negative, it means the collector surface become soiled. Note that the positive ΔSR values due to cleaning were deleted and linearly interpolated to quantify only the effect of soiling accumulation.

Manual cleaning of the mirror sample of the TraCS device was performed approximately every two weeks to prevent saturation of the mirror surface by the accumulated soiling (See Fig. 3).

2.2. PV Soiling Measurement

In order to quantify the effect of soiling on PV technology, a DustIQ soiling sensor from Kipp & Zonen [28] was used in this study (Fig. 4). The DustIQ measures the soiling of photovoltaic panels using optical soiling measurement (OSM) technology that measures using a photodiode the scattered LED light it receives from the accumulated soiling particles on top of its glass panel. With a built-in calculation unit, the transmission loss TL due to soiling is determined. In the case of PV, SR is defined as the fraction by which the transmittance efficiency of a PV glass is reduced due to soiling, and is calculated internally (Eq. 4).

$$SR = 1 - TL \tag{4}$$

The DustIQ measures soiling without the need for daily manual cleaning or moving parts, and without using the sun's irradiance, it is therefore independent of the sun's angle of incidence (AOI) and sky conditions, and it can also operate at night [28,47,48]. The sensitivity of the DustIQ depends strongly on the type and the color of dust, which makes it necessary to perform a local dust calibration to adjust its sensitivity [28]. To do this, the DustIQ is equipped with an on-board polycrystalline silicon cell. When the optical sensors of the DustIQ are soiled, the short circuit current in the silicon cells and the scattered light are measured internally before and after cleaning. The internal calculation unit determines the sensitivity that corresponds to the local dust and the DustIQ measures the transmission loss due to local soiling [48]. Field tests of the DustIQ sensor have already been conducted by the manufacturer in many dusty regions, including Morocco and Spain [47]. The field test showed that the DustIQ data agrees well with the soiling data derived from a pair of reference cells and a pair of PV modules. Therefore, the DustIQ is a good solution for measuring PV module soiling. The sensing area used by the DustIQ to measure soiling has a circular form with a diameter of about 4 cm. The problem with small sensing area soiling sensors is related to cleaning. This still needs to be investigated to evaluate the ability of small sensing area sensors such as DustIQ and Mars to quantify the actual impact of natural cleaning events on PV installations.

During the measurement campaign, the SR was measured with a time step of one minute to be in-line with the International Electrotechnical Commission (IEC) 61724-1 international standard for photovoltaic system performance monitoring recommendations [49]. The DustIQ is sensitive to dew formation, for this reason only the average value of the data between 11am and 3pm were selected when for sure no dew is presented above the sensor surfaces.

However, PV modules soiling loss depends on the sun angle of incidence (AOI) and lighting conditions as caused by clouds or haze. Wolfertstetter et al. [48] proposed a method to correct the soiling measurement performed by incidence-angle independent optical soiling sensors like DustIQ, by using the incidence angle and Linke turbidity, derived from the global horizontal irradiance (GHI) and direct normal irradiance (DNI) measurements, as inputs to the adaptation function. The method can improve the solar plants yield prediction. This correction has not been applied, since the purpose of this work is to evaluate the optical losses of solar collectors due to soiling. This correction will be more relevant in the assessment and simulation of solar photovoltaic installations by including the SR not as a daily average but as a parameter that varies over the course of the day (depending on AOI).

The DustIQ is made up of two independent sensors (see Fig. 4), which when mounted vertically, will give different soiling measurements SR_1 and SR_2, as soiling is rarely uniform, and this is due to gravity and the morning dew flow taking away some of the soiling which can also be seen in the real PV panels [50]. As described in Fig. 5 soiling tends to accumulate at the bottom side of the PV modules.

To calculate the daily soiling ratio SR, the mean of two DustIQ sensor readings SR_1 and SR_2 is considered (Eq. 5).

$$SR = \frac{1}{N}\sum\nolimits_{h=11a.m}^{3p.m}\frac{SR_1 + SR_2}{2} \tag{5}$$

Fig. 6(a) displays the soiling ratio measured by the two sensors for a part of the data used in this work; Fig. 6(b) shows the measured SR after data processing mentioned in this section. The ΔSR was also calculated in the case of PV using the same method described in the previous section.

Table 1
Meteorological station sensors specifications.

Parameter	Sensor	Measurement range	Accuracy
Temperature	Campbell Scientific CS215	- 40°C to +70°C	±0.3°C at 25°C ±0.4°C over +5°C to +40°C ±0.9°C over - 40°C to +70°C
Relative humidity	Campbell Scientific CS215	0% to 100%	±2% over 10–90% ±4% over 0–100%
Wind speed	NRG #40CAnemometer	1 to 96 m/s	<0.1 m/s over 5–25 m/s
Wind direction	NRG #200P Wind vane	0° to 360°	<1%
Precipitation	Tipping bucket rain gauge Young 52202	0.1 mm per tip	±2% up to 25 mm/h ±3% up to 50 mm/h
Barometric Pressure	Campbell Scientific CS100	600 hPa to 1100 hPa	1 hPa over 0°C to 40°C 1.5 hPa over -20°C to +50°C 2.0 hPa over -40°C to +60°C
GHI & DHI	Kipp&Zonen CMP21 pyranometer	0 W/m^2 to 4000 W/m^2	±2%
DNI & Reflected DNI (TraCS)	Kipp&Zonen CHP1 pyrheliometer	0 W/m^2 to 4000 W/m^2	±1%

Fig. 5. Soiling distribution on a PV system installed at the Green Energy Park.

Fig. 7. High precision meteorological station installed at the Green Energy Park.

2.3. *Measure of meteorological parameters*

The meteorological data parameters were collected from a meteorological station (see Fig. 7) consisting of multiple high-precision sensors, as listed in Table 1 [51–57].

3. Results & Discussion

3.1. *Comparison of soiling effect on CSP & PV*

The daily SR from 15/06/2018 to 22/07/2018 for both CSP and PV, measured by TraCS and DustIQ are presented in Fig. 8. It can be seen that the SR measured with the TraCS system shows a steeper decrease compared to the one measured with the DustIQ sensor. Therefore, the effect of soiling on the CSP is more significant than on the PV.

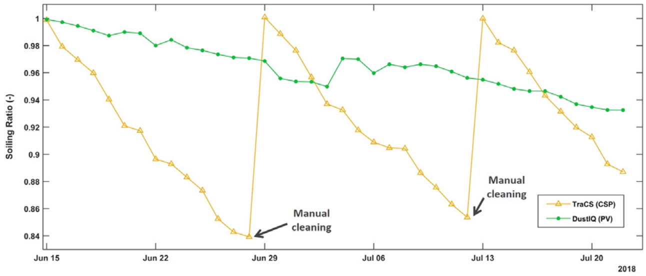

Fig. 8. Daily average soiling ratio values measured by TraCS (CSP) and DustIQ (PV) at the Green Energy Park (BenGuerir, Morocco) from 15/06/2018 to 22/07/2018.

Fig. 9, illustrate the calculated daily average ΔSR for both (a) PV and (b) CSP technologies. As it can be seen from Fig. 9, the ΔSR follows the same tendency for both technologies, but it is mostly higher for the TraCS system than for the DustIQ measurements. This means that the optical efficiency of CSP solar collectors tends to decrease faster than that of PV collectors. Therefore, the PV glass transmittance is much less sensitive to soiling than the CSP mirror reflectance. It is well known

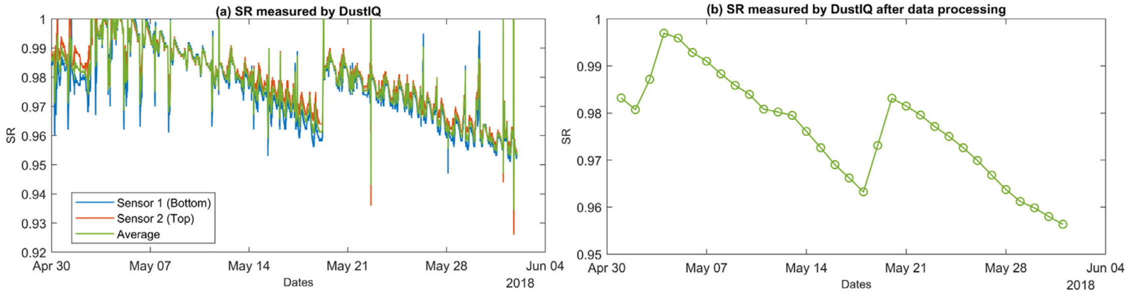

Fig. 6. (a) Soiling ratio measured by sensor 1 and sensor 2 of the DustIQ, and the average value of the two measurements; (b) The DustIQ measurements after data processing.

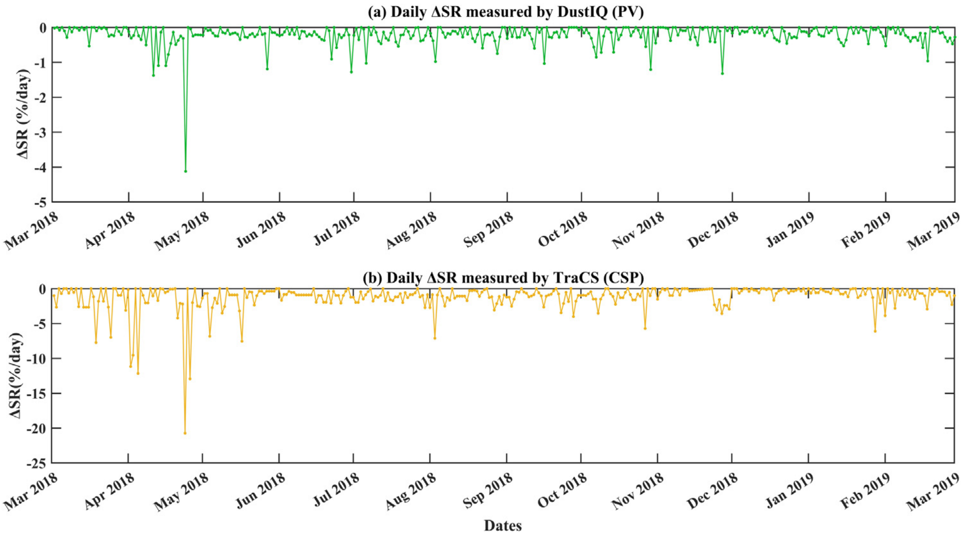

Fig. 9. The daily soiling rate ΔSR (%/day) measured by DustIQ (PV); (b). The daily soiling rate (ΔSR) measured by TraCS (CSP).

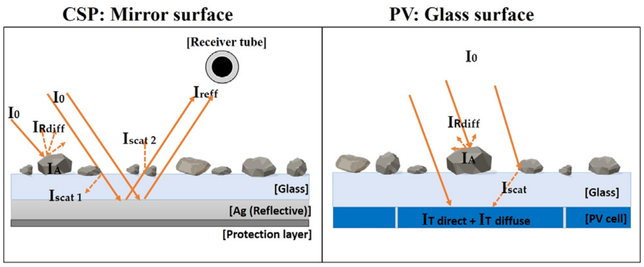

Fig. 10. The pathway of the incoming solar rays throughout the soiled layer of CSP mirror (left) and PV glass (right).

that the soiling phenomenon has a high spatial and temporal variability [6,58]. Thus, there are days with very high soiling accumulation rates (strongly negative values of ΔSR). While other days are characterized by very low soiling accumulation (ΔSR with approximately zero values). Note that in this study, in case of CSP technology, only the soiling of the mirror surface has been quantified using a TraCS sensor. The soiling effect for a specific CSP plant might differ from the TraCS measurement. For example, the soiling of the glass envelopes of the receiver tubes can reduce their transmittance and hence the overall CSP system efficiency as well [59]. The position of the mirrors in the solar field has a noticeable influence [60], their tilt angle influences the soiling rate strongly [61], the angle of reflection and the incidence angle change the soiling ratio [62] and the scattering related losses are also stronger for CSP plants with smaller opening angles [63]. In PV systems, it has been found that the soiling rate of PV modules is not only influenced by the site climate, but also by their tilt angle and whether they are installed on a fixed or tracked system [64].

The difference between the efficiency loss due to soiling in CSP and PV can be explained by the optical properties of the surface of each sample, whether it is a mirror or transparent glass, as well as the different pathways of the incoming rays until it reaches the absorber. As it can be seen in Fig. 10, for both technologies, the incoming irradiance I_0 is partially transmitted, absorbed or scattered by the soiled layer. In case of CSP, I_0 is partially absorbed I_A, scattered backwards I_{scat} and diffusely reflected I_{Rdiff}. In a CSP plant, only the specular reflected irradiance reaches the receiver tube I_{reff} (small acceptance angle). In the case of a PV collector, only light absorbed by the soiling particles I_A and diffusely reflected light I_{Rdiff} is lost, while the direct and diffusely transmitted light ($I_{T\ direct} + I_{T\ diffuse}$) reach the absorber (much wider acceptance angle), which means most forward-scattered light can be used for electricity production [38].

3.2. Extreme Events: Dust Storms and Red Rain

During the period of study, the ΔSR was very high at certain days (Fig. 9). ΔSR measured with the TraCS device reached up to -20 %/day which means a CSP mirror reflectance drop of 20%. For the PV collector transmittance, ΔSR of more than -4 %/day has been measured with the DustIQ device. This can be explained by light rain in combination with high atmospheric dust concentration recorded between April 20 and 21, 2018 (0.1 mm and 1.6 mm, respectively), as shown in Fig. 11. The forecast of the NMMB/BSC-Dust or BSC-DREAM8b model operated by the Barcelona Supercomputing Center (Fig. 12) shows that high dust-loads in the lower atmosphere have been modeled for BenGuerir (Morocco) between April 20 and 21, 2018 (see Fig. 13). This phenomenon is known as "red rain", which is common in arid and semi-arid regions of Morocco [7,36,39,46]. The drastic impact of red rain on the efficiency of solar collectors has also been reported by other studies and reviews for other regions [60,65]. However, high dust deposition rate may still be happening within several days after the event due to dust suspension and re-suspension. Consequently, soiling is a complex phenomenon that depends on many parameters and that rainy days are not always related to cleaning or low soiling rates, as different types of precipitation can have a range of effects, good or bad. This effect depends not only on the total amount of daily rainfall but also on the intensity of the rain [66]. Not to mention the interaction between the other environmental conditions that can define the soiling rate [67,68].

To study the effect of soiling on the performance of CSP and PV during the dry conditions, the average daily ΔSR during dry period from 1st June to 1st September was calculated. In these 3 months dry period, the average ΔSR is -0.22 %/day for PV and -1.12 %/day for CSP. Therefore, even without precipitation, the soiling loss is lower than the soiling loss in the period between March 2018 and June 2018 (with dust loaded atmosphere and red rain events). The red rain event can cause a considerable performance drop in solar energy plants, more than the performance drop if no cleaning is done during a dry period, especially for CSP solar plants. These red rain events lead to the drop of dust particles on the surface of the solar collectors, and make them stickier and not easily resuspended by wind or rain, which will lead to higher O&M costs (see Fig. 14), because the cleaning after red rain events requires extensive water and labor to achieve the optimal efficiency of solar power plants [69,70].

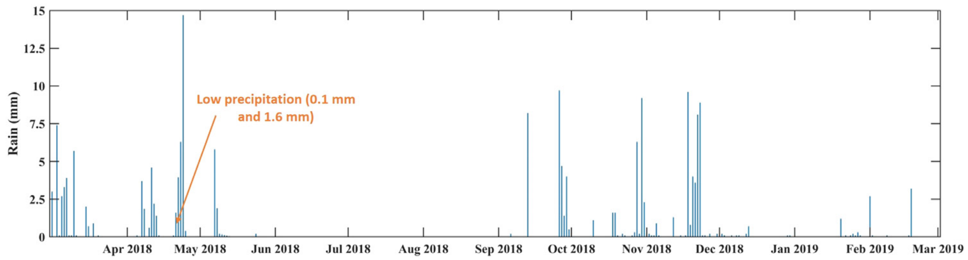

Fig. 11. Recorded daily rain sums (mm) in BenGuerir from March 2018 to March 2019.

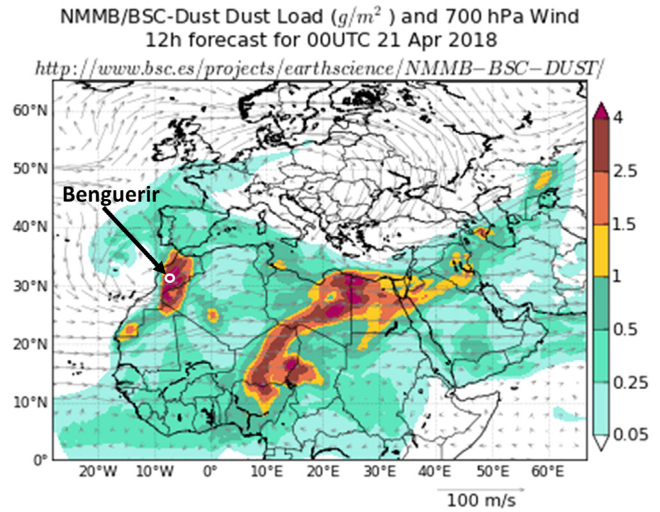

Fig. 12. Barcelona Supercomputing Center (BSC): dust forecasts for April 21,2018. Data and/or images from the (NMMB/BSC-Dust or BSC-DREAM8b) model, operated by the Barcelona Supercomputing Center (http://www.bsc.es/ess/bsc-dust-daily-forecast/).

Fig. 13. Dust loaded atmosphere & Dust storms recorded between 20th and 21 April 2018 at Green Energy Park (BenGuerir).

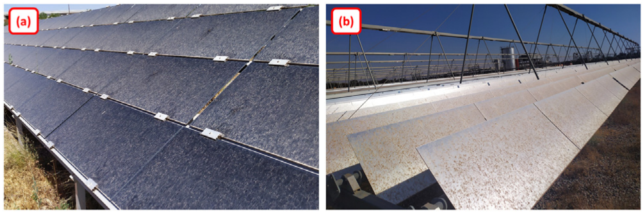

Fig. 14. (a) PV system & (b) CSP system (LFC) after a red rain event at the Green Energy Park.

3.3. *Soiling seasonality*

In order to get an idea of the seasonality of the soiling impact on CSP and PV technologies, the monthly average of the ΔSR during the entire period of one year (March 2018 to March 2019) was calculated. As only one year is evaluated, the extracted seasonality is only an estimation as differences between different years are possible. The monthly average ΔSR is simply calculated by averaging the daily ΔSR during each month, while the annual average soiling rate is calculated by averaging the daily ΔSR for the entire one-year study period. As it can be seen in Fig. 15, for PV, monthly average of soiling rate is approximately between -0.083 %/day, and -0.36 %/day with an annual average of -0.23 %/day. For CSP mirrors the monthly average of soiling rate is approximately between -0.26%/day, and -3.04 %/day with an annual average of -1.18 %/day. The average soiling loss in BenGuerir has therefore been found to be around 5 to 6 times higher for CSP compared to PV. For some intervals, significantly higher factors between CSP and PV soiling rates are found (e.g. about 10 in April 2018). Other factors have been reported in previous studies. For instance, the measurement campaign conducted by Bellmann et al [38] reveals that the soiling rate is 8 to 9 times higher for CSP mirror compared to PV glass, with a soiling rate of -0.35%/day and -0.04%/day for CSP and PV, respectively. Which means that the solar collectors optical efficiency loss is higher in BenGuerir (Morocco) compared to Valverde (Portugal). This different result can be explained by the site climatic conditions of the studied site, the measurement methodology and the period of study.

The impact of soiling on the CSP and PV systems was more significant during the month of April, due to the extreme events that occurred during this period, such as dust storms and red rains. However, the soiling loss is still high during the dry period, which is expected, since the city of BenGuerir is located near the Sahara Desert, which contributes to a higher concentration of particulate matter in the air (see Fig. 15), which can lead to higher deposition of particulate matter on the solar collectors [69]. Aerosol optical depth (AOD) is defined as the aerosol suppression coefficient of the accumulated points in the vertical direction, and it can be used as a quantitative estimate of the amount of aerosols contained in the atmosphere [71,72]. Dust AOD was stated to be one of the parameters that explain the soiling behavior [73–75]. It can be seen in Fig. 16 that the modeled dust AOD values from the CAMS-AOD Copernicus database are significantly higher during the period from July to November 2018 in comparison to e.g. December 2018 to February 2019. This could be the cause for high soiling rates during July to Novem-

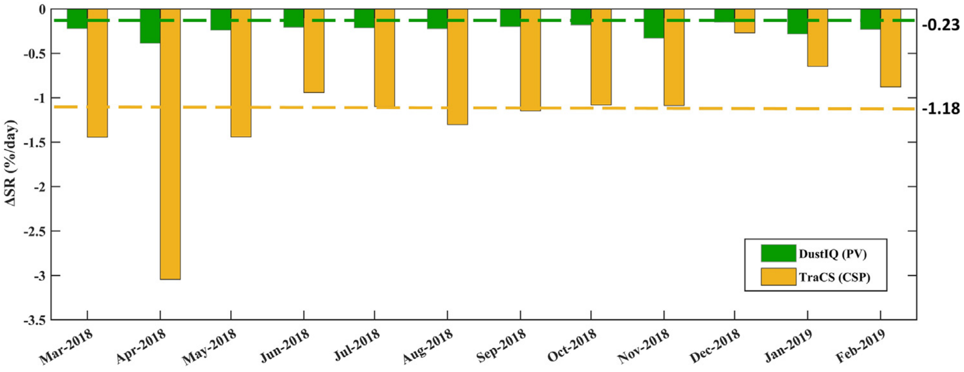

Fig. 15. The monthly average daily of soiling rate ΔSR (%/day) from TraCS (CSP) and DustIQ (PV) in BenGuerir.

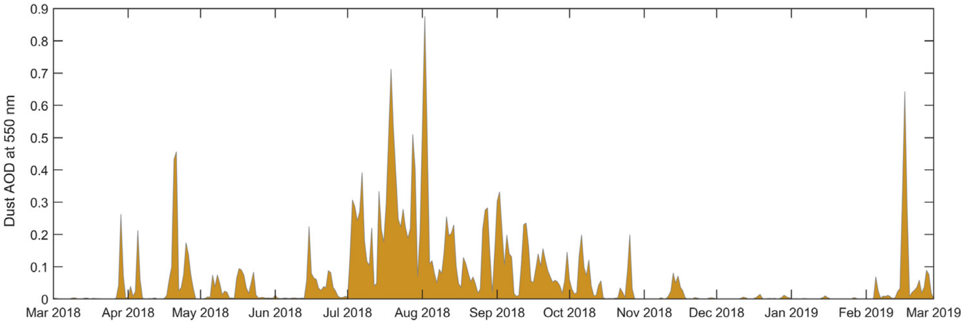

Fig. 16. The daily average of dust aerosol optical depth (AOD) at 550 nm for BenGuerir. This data was extracted from CAMS-AOD Copernicus database and provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (http://www.soda-pro.com/web-services/atmosphere/cams-aod).

ber 2018 and lower soiling rates between December 2018 and February 2019.

4. Soiling mitigation solutions

As shown in the previous section, soiling is an important loss factors for the performance of both CSP and PV technologies. Nevertheless, many approaches have been developed to reduce the effect of soiling, such as anti-soiling coatings (ASCs). However, the effectiveness of ASCs depends on the composition and properties of the dust at the site, as well as local weather conditions. This approach does not totally solve the soiling problem, as it only reduces the impact of soiling by enhancing self-cleaning ability of solar collector surfaces, and the energy loss due to soiling of coated solar collectors still can reach significant values [76–78]. The design of the solar plant (orientation and tilt angle) is also an important criterion that determines the impact of soiling on performance. Studies such as [79–82] have shown that the soiling level is highly dependent on the tilt angle of solar collectors, as it significantly decreases with a steeper surface tilt angle. Vertical or inverted night stowage has also been suggested in literature as a soiling mitigation technique [64,80,83]. Electrodynamic dust screens (EDS) consist of generating a dynamic electric field from interdigitated electrodes embedded in the protective film, supplied with alternating high voltages across the surface of the solar collector [84]. EDS has been shown to be a successful anti-soiling technology for PV and CSP at laboratory scale. However, in the field the outdoor conditions have an impact on the electronic systems. Further, high relative humidity and dew formation alter the soiling layer properties (cementation, caking or capillary aging) which reduces the effect of EDS [85,86]. Additionally, EDS is costly and poses safety issues, especially during rainy conditions [87]. Until now, cleaning of solar systems is still mandatory with different frequencies dependent on the site, as it is the only way to fully recover the optical efficiency of solar collectors. A low cleaning frequency might result in a soiling layer which is harder to be removed. Dependent on the cleaning technology, it can also cause scratching or abrasion of anti-reflective coatings (ARCs) [88,89]. There are three main categories of cleaning systems: manual, semi-automatic and fully automatic. A supplementary classification can be made between these systems, namely dry and wet cleaning [86,90]. Dry cleaning is becoming increasingly used, especially as most large-scale solar power plants are located in desert, arid and semi-arid regions, where water is scarce [91]. Wet cleaning is typically preferred due to its enhanced efficiency and lower damage risk [92], and it is mostly applied in areas where water is available. In general, most CSP installations use wet cleaning, as the risk of damaging the solar mirrors by using dry cleaning is quite high [4]. In the case of PV, dry cleaning is less effective than wet cleaning, but it is more advantageous in the case of installations located in regions with limited water availability [93]. Nevertheless, the choice of the best cleaning method is a strategic decision that will affect the profitability of the solar power plant and it depends on many parameters in terms of technical and economic aspects [90]. For instance, the type and composition of local soiling, the soiling deposition rate, the system design (e.g., tracking or fixed angle, roof or ground mounting), the labor and water costs and the required equipment. Sometimes, contract conditions can also have an influence on the choice of cleaning method, as in some regions, solar projects are required to adopt manual cleaning in order to create employment opportunities for the local community. It should be noted that the selected cleaning solution should be compliant with solar collector's manufacturer's warranty. Identifying the optimal cleaning schedule is also important in order to maximize the solar plant performance and, at the same time, minimize the cleaning costs [13,94].

5. Conclusion

To accurately plan solar power plants in Morocco, the influence of soiling on the performance of different solar technologies under the Moroccan climate is required. The soiling phenomenon is one of the major parameters especially for Morocco, since for solar energy relevant regions in the country are usually considered arid and semi-arid.

Many studies have been done regarding the effect of soiling on PV and CSP technologies separately, especially by using glass and mirror samples, but not much of them evaluate and compare the effect of soiling on both technologies simultaneously and under the same conditions by using soiling monitoring systems for CSP and PV. This study evaluated the effect of soiling on both CSP and PV technologies simultaneously and under the semi-arid climate of Morocco. TraCS and DustIQ soiling sensors have been installed at the Green Energy Park research facility in BenGuerir city of Morocco to measure the soiling loss of CSP and PV respectively for a period of one year (March 2018 until March 2019). It was found that the annual average soiling rate of - 0.23 %/day was measured by DustIQ and -1.18 %/day by TraCS. Which means that the averaged soiling rates measured with the TraCS device have been about 5 to 6 times more than measured with the DustIQ sensor. Therefore, it can be concluded that CSP power plant performance is in general much more affected by soiling than PV power plants. A period with red rain events during April 2018 was also investigated. It was found that this period recorded the highest soiling loss throughout the year. The soiling rate exceeded -20 %/day of the CSP mirror reflectance and more than -4 %/day of the PV glass transmittance in one day during this extreme red rain event. The maximum soiling loss recorded during the dry period in August 2018 when no precipitation events occur has been observed to be around -1.4 % for PV and -7 % for CSP. Even during the dry period, the soiling loss is lower than the soiling loss when the red rain event occurred. The difference between the impact of soiling on CSP and PV technologies can be explained by the optical properties of the surface of each collector, as well as the irradiance trajectory that goes through the soiled layer.

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