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Research article

Experimental study on the impact of soiling on the modules temperature and performance of two different PV technologies under hot arid climate

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ABSTRACT

In this paper we conducted an experimental study to evaluate the impact of soiling on the temperature and electricity production of two photovoltaic technologies (Poly-Si and CdTe) under a hot semi-arid climate of Morocco. For this purpose, two modules -from each technology-were exposed for one year where one is cleaned every day and the other is left to accumulate soiling on its surface. In parallel, the electrical parameters, the weather data and the modules temperature were monitored using high precision instruments. Results show that the Poly-Si technology is highly affected by soiling in comparison to the CdTe where the measured daily Soiling ratio (SR) can reach 0.70 and 0.73 respectively. This values lead to a drop on the energy production of 15% for the Poly-Si and 13%. Regarding the modules temperature (Tm) results show that soiling has an impact on increasing the temperature for both technologies, but the Poly-Si module is more affected than the CdTe one, where the daily average temperature difference between the clean and the soiled modules is around 1.5 °C and 1.3 °C for both technologies, respectively.

1. Introduction

Generally, the best locations to host solar power plants are the ones blessed with high irradiation records. These locations are mostly located in the so-called Sun-belt, where most of the sites are characterized with an arid desert climate [1]. In addition to the high solar potential, this climate is known with the high temperature records and the presence of dust and sand [2, 3] which presents a limitation for the operation of the solar power plants [4]. The soiling impact on the solar plants may cause two different degradation modes: (i) reversible and (ii) non-reversible.

For the first degradation mode, the deposited dust on the PV modules surface causes a drop in the optical properties of this last, therefore, a drop in the electricity production [5]. Indeed, several studies have been published in the literature and reporting different power losses. For instance, Gostein et al [6] reported a 9.6% of losses in the power of Poly-Si module after 9 months of exposition under the US Southwest area climate. Similarly, Cordero et al [7] measured a soiling losses reaching 39% after one year exposition in Atacama deserts of Chile. In the same context, and based on an experimental investigation conducted by Micheli et al [8] in Granada (Southern Spain), the measured power losses reaches 23% after one year of exposition. For more details about the power losses in different locations, we recommend the following paper [9].

To resolve the issues caused the first degradation mode, a cleaning event is usually sufficient to reverse the problem and getting the power production, of the PV modules, to the its initial state, even by the mean of manual cleaning [10], robotic cleaning [11] or a natural cleaning mode using rainfall or the dew [12].

Regarding the second degradation mode, it can be manifested in different ways like the appearance of scratching on the glazing surface or coating due to the frequent contact between sharp mineral particles and the surface during cleaning or during sand storms [13, 14, 15]. In addition to that, soiling can cause a partial shading with non-homogenous distribution of the dust on the modules temperature [16]. This issue causes an increase on the modules temperature due to the leakage current, which may cause an immediate drop on the modules efficiency [17] and if remain for long-term, it can drive to the apparition of hot-spots which is one of the most detected and reported default in the arid regions [18, 19, 20, 21].

In the literature, the main focus of the most papers dealing with soiling is oriented even to: (i) the measurement of the soiling rate in

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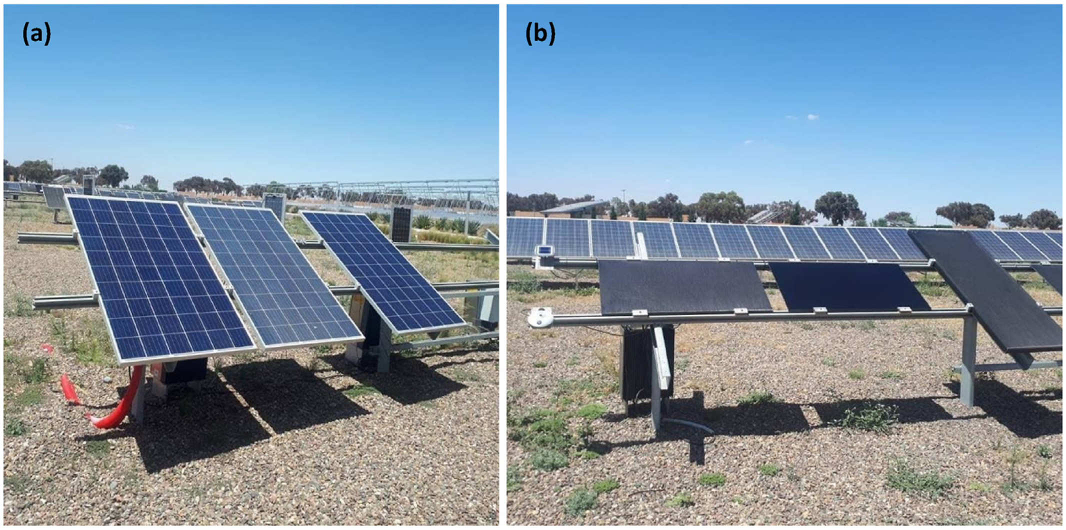

Figure 1. The experimental setup used the assess the soiling impact on the modules temperature.: (a): the Poly-Si modules. (b): the CdTe modules.

different locations [22, 23, 24, 25, 26, 27] and for different technologies [28, 29, 30], (ii) the proposition of the optimal cleaning modes and strategies [31, 32] and the proposition of some novel soiling measurement devices [33, 34, 35].

Nevertheless, very few are the papers dealing with the impact of soiling on the modules temperature. Costa et al [36], presented an assessment of soiling impact on the Si and CdTe technologies in different locations in Brazil. They found that the temperature of the CdTe modules is less affected by soiling than the one of the Si technology due to the non-homogeneity distribution of the dust. Nevertheless this study has been conducted under equatorial climate where soiling is not that high (generally between 1 and 0.9 during the dry period) due to the frequent rainfall.

In the current study, we conducted a one year experience to evaluate the impact of soiling on the module temperature under the semi-arid climate of Morocco. For this reason, two modules from two technologies (Poly-Si and CdTe) were exposed under outdoor conditions where (for each technology) one of the modules is cleaned on a daily base and the other is left without cleaning.

Results show that soiling is an important issue for our field of study where the drop can reach 30% during the dry period of the year. Besides, the Poly-Si technology is more affected by this phenomenon than the CdTe. Regarding the modules temperature (Tm), we found that the Tm measurements -from both technologies-show a good agreement with the dust accumulation and that Poly-Si is the one affected by the Tm in comparison to the CdTe.

The paper is organized as follow: the next session is dedicated to present the experimental protocol and the methodology used, after that, the results section will firstly present and discuss the soiling impact on the PV modules performance, next, a detailed analysis of the Soiling Ration measurements will be presented finally the impact of soiling accumulation will be presented and with the introduction of a new equation for the prediction of the modules temperature based on the soiling ratio measured in a specific location.

1.1. Material & methodology

In order to assess the soiling impact on the PV modules temperature, an experimental setup has been built. This setup consists of four PV modules, two of them are Poly-Si with a nominal capacity of 260 Wp and the others are CdTe modules with a capacity of 115 W_p (see Figure 1).

For both technology pares, a similar cleaning schedule has been conducted, where one module from each technology is daily cleaned (to be considered as a reference module) and the other module is left without cleaning to accumulate the dust and soiling naturally. The four modules were exposed for a period of one year under the arid climate of Benguerir (32°15′20.6°N,- 7°55′42.2°E).

The field of study is considered as an attractive site for the installation of solar power plant due to the high amount of solar irradiance that can reach 2240 kWh/m$^{2/}$year [37]. Besides, this location has similar weather conditions to other sites that are already hosting PV power plants (like Ourzazate), thus, the results of the current experiment can be representative to the operators of these plants.

Figure 2 displays the daily sums of the hourly POA irradiation measured in-situ. To measure the POA we used a Hukseflux SR20

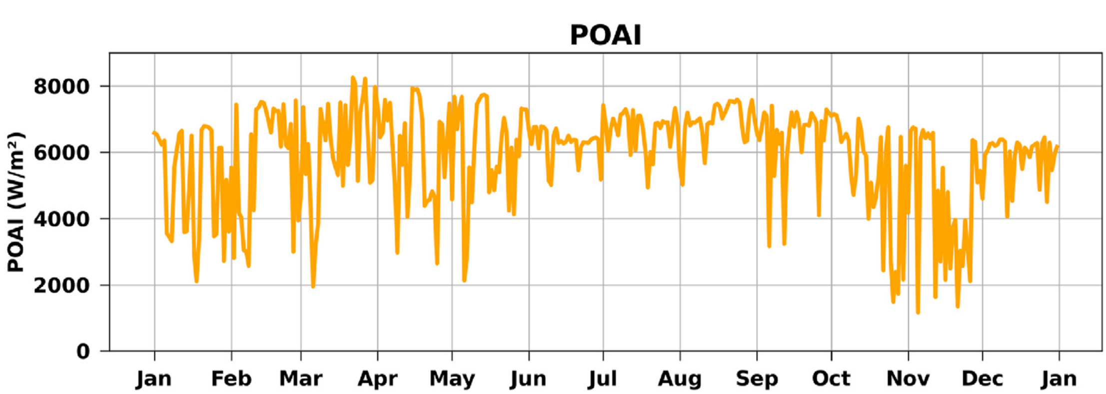

Figure 2. Daily sums of the hourly POA irradiation measured in-situ.

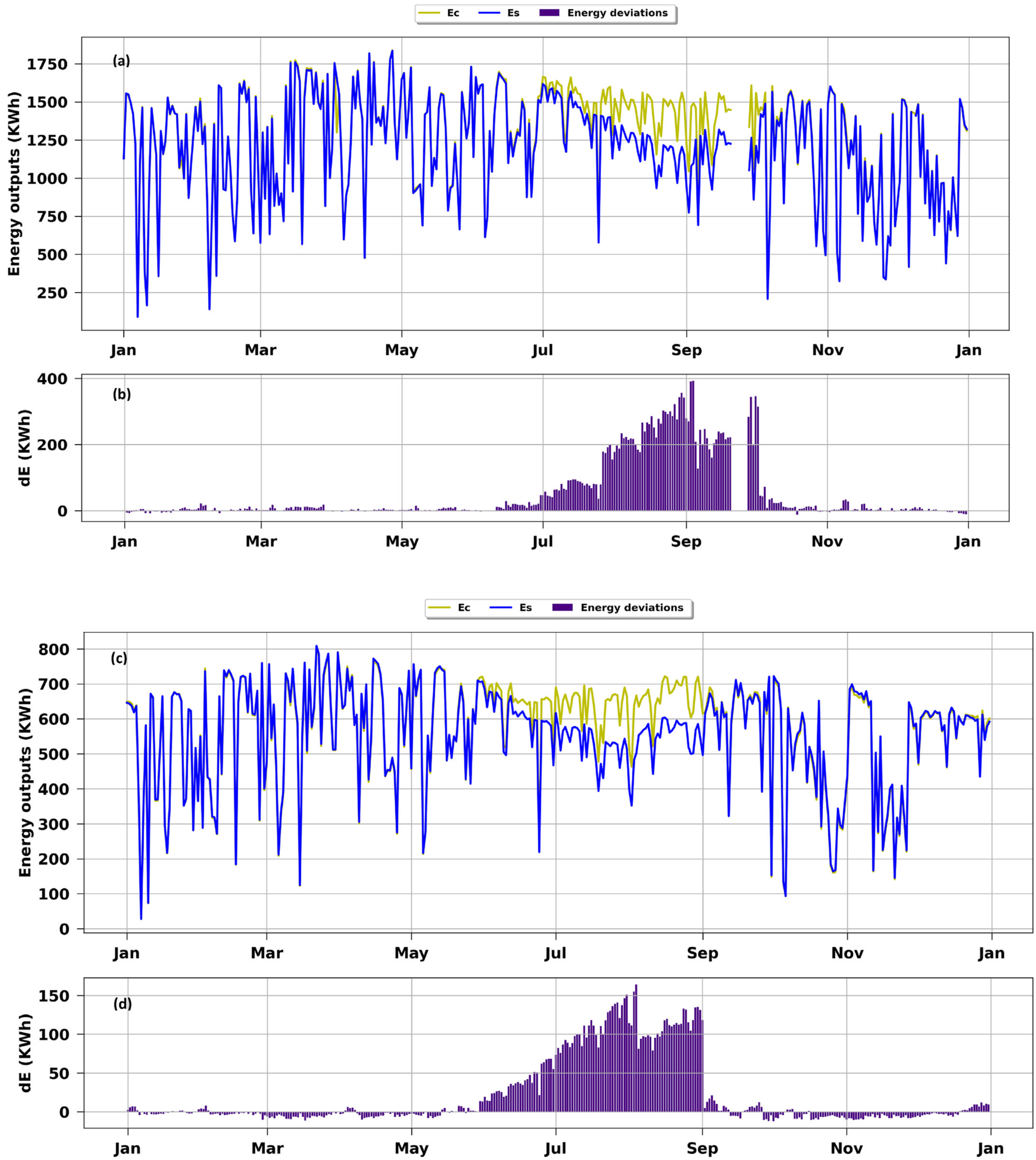

Figure 3. Production performances of the investigated PV panels: (a) The electrical output of the Poly-Si modules (b) yield deviation between the clean and the soiled Poly-Si modules (c) The electrical output of the CdTe modules (d) yield deviation between the clean and the soiled CdTe modules.

pyranometer. The SR20 is a secondary standard ISO 9060 thermopile which is considered as a high-quality Irradiometer that provides the solar irradiance values with an error of 2% for the daily sums. Back to Figure 1, it is clear that the highest amount of solar irradiance is received between April and September and the corresponding daily values vary between 5 kWh/m^2 and 8 kWh/m^2. As for the fall and winter, the POA values can be considered as cheeky/intermittent and the minimum daily records can reach some values around 1 kWh/m^2, especially during November and December. Nevertheless, with an average daily POA values reaching 7 kWh/m^2, we can say that in general the received irradiation during that time is favorable for a good operation of the PV power plants.

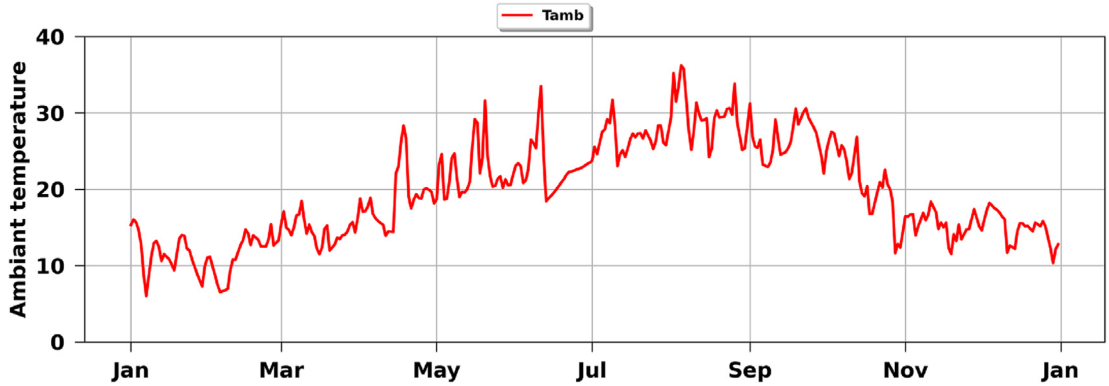

Figure 4. Daily ambient temperature.

In order to measure the modules temperature, the SOL. Connecte thermal sensor has been used. This sensor is a Platinum resistance PT1000 B with a measurement range from −35 to 105 °C. For our experiment, a thermal sensor was installed in the middle of the back-sheet of the four PV modules enabling the monitoring of the temperature values each 10 s.

Regarding the electrical parameters of the inspected PV modules, we used an MPP meter card for the measurement and the monitoring of these parameters. This MPP card monitors the IV-characteristics (V_{oc}, I_{sc}, V_{mpp} and the I_{mpp}), as well as, the Irradiance and the module's temperature with high accuracy. The measured data are saved afterword's in a server via a SCADA system. To ensure a high performance of the measured data, we use a daily accuracy check and quality control protocol for the measurements.

In what follows, we will present the results of the experiment including the assessment of the electrical output and different technologies, the soiling impact on their performances, as well as, the link between the soiling accumulation and the modules temperature will be presented in the next section.

2. Results and discussion

2.1. Soiling impact on the electrical outputs

As described above, Figure (3a & 3b) presents the daily sums of the power output for the CdTe and the Poly-Si modules respectively. For the clean modules, it can be observed that a considerable amount of energy can be produced over the year. This is completely reasonable due to the high amount of the POA irradiation received by the field of study. However, during the dry period of the year (between May and September) a significant drop on the production can be observed despite the available high solar irradiance. This is mainly due to the high temperature values that affects the electrical production during this period (see Figure 4).

This drop is even more significant for the soiled modules where the deviation between the two modules can reach 160 kW_eh for the CdTe and 400 kW_eh for the Poly-Si technology (Figure 3).

From the above results the one can see the direct impact of soiling on the PV modules which is mirrored by a drop in the electrical output. Nevertheless, for long-term exposition, the accumulation of dust on the modules surface may lead to more complicated problems, mainly the degradation of the modules [38]. In fact, a long-term deposition of dust/soiling on the modules surface can lead to a partial shading of the cells, thus, the appearance of leakage currents leading to the creation hotspots. For this reason, the main objective of this study is to evaluate the behavior of the modules temperature versus soiling for both CdTe and Poly-Si technologies. Nonetheless before discussing the impact of soiling on the modules temperature, we need to assess the soiling rate measured in our field of study.

2.2. Soiling rate measurements campaign

In the field of solar energy, Soiling is defined as the accumulation of dust, sand and organic matters on the surface of the PV modules or the mirror reflectors. This deposition lead to a significant drop in energy -as presented above- and may also cause some degradations of the solar plants components. Soiling is a site specific problem and it depends on several weather conditions mainly Rain and the particle/Aerosols load in the lower atmosphere [39].

Figure 5, presents the daily averages of the precipitations and the Aerosols Optical Depth (AOD) measured in our field of study. As it can be noticed, during the period between April and September -the period with high electrical drop due to soiling deposition-our field of study is characterized with a lack of rainfall and a higher aerosol with a

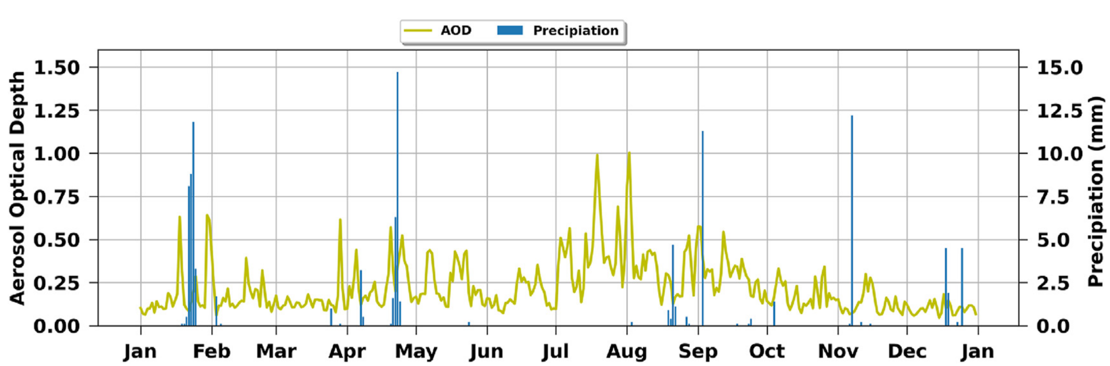

Figure 5. Daily variation of AOD and Rain.

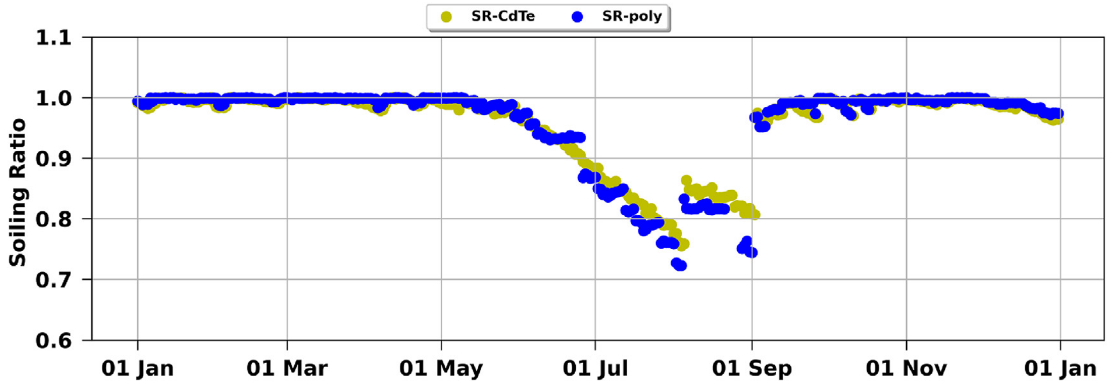

Figure 6. Daily soiling ratio measurements from the Poly-Si and the CdTe modules.

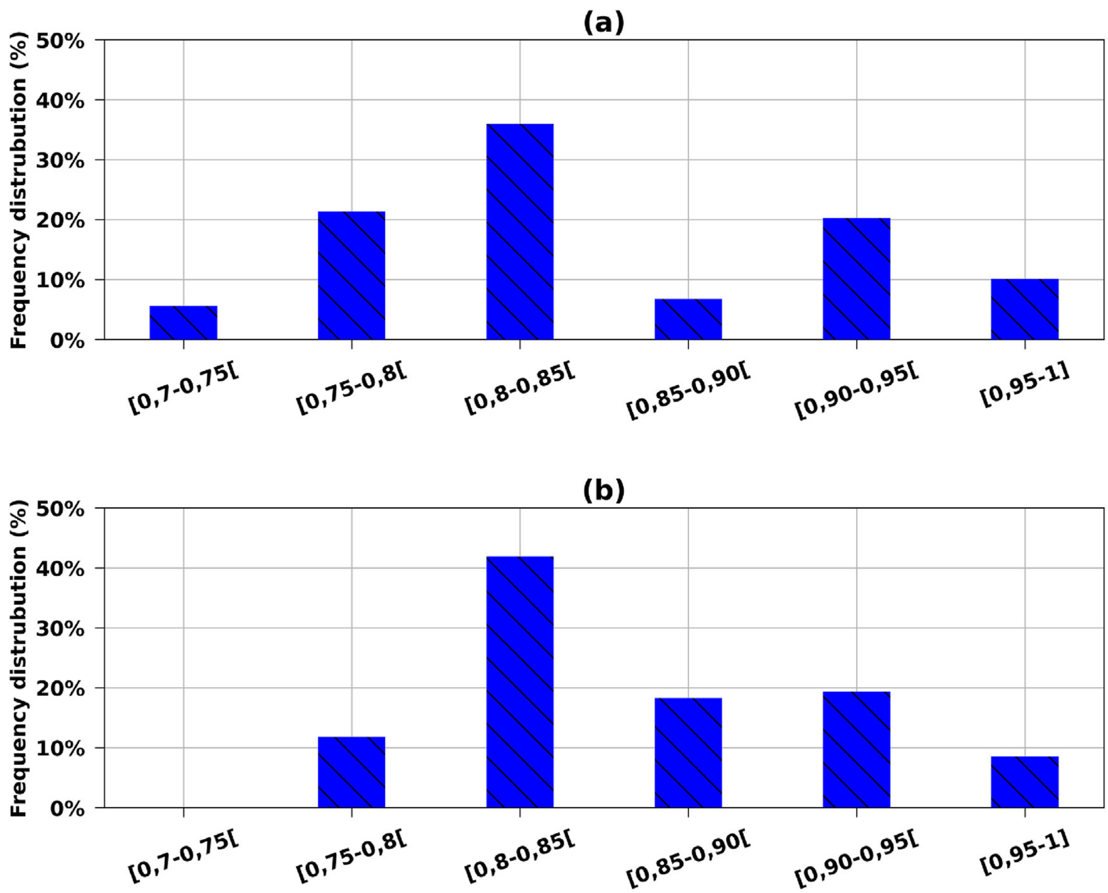

Figure 7. Soiling rate Frequency distribution: (a) poly-Si technology (b) CdTe technology.

concentration aerosol transparency metric reaching one. This later is generally due to the long dust particles transportation from the African desert [40]. However, along the wet period, the aerosol transparency metric is less than 0.30 except for some peaks that reflect usually the some red rain events characterizing the site during Fall and spring [41].

As for the precipitation, this parameter can play the role of a natural cleaning agent for the PV modules if higher values are recorded. For our field of study, it is clear that the rainfall are rare, but some picks have been recorded during August and September which contribute to a rise in the power production of the soiled modules. This rise is appears clearly as a jump in the Soiling Ratio (SR) presented in Figure 6.

The Soiling Ratio (SR) is a metric used to quantify the soiling effect on the PV modules [25]. To calculate the SR researchers usually use the short circuit current (I_{sc}) as it is directly proportional to the amount of the solar irradiance received by the module's surface. So, the highest amount of dust on the top of the surface, the less is the irradiance reaching the cells, thus, a drop on the electricity production.

In this study, the SR for both technologies has been calculated using Eq. (1):

$$SR = \frac{Isc(soiled)}{Isc(clean)} \tag{1}$$

where Isc (Soiled) is the short circuit current of the soiled module and the Isc (clean) is the short circuit current of the clean module. Note that an SR = 1 means that the investigated modules is clean, thus, no soiling losses can be measured. The daily SR values are presented in Figure 6.

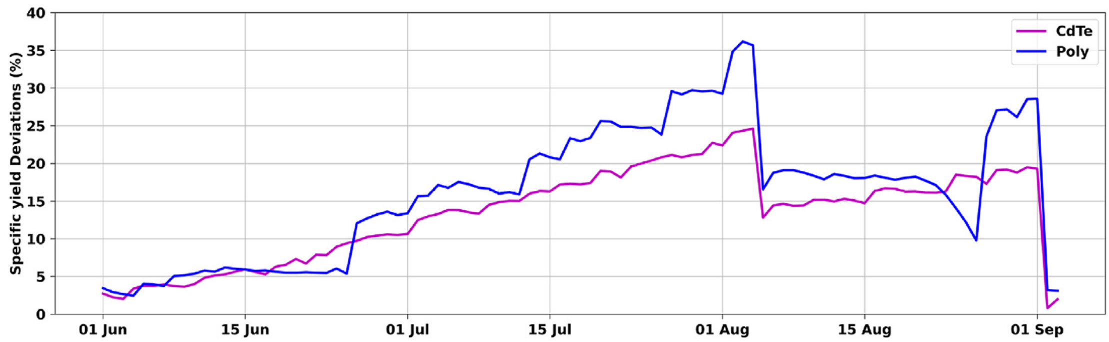

Figure 8. Specific yield deviations for CdTe and poly-Si during the dry period.

From Figure 6, and for both technologies, we can observe that the SR profiles can be split into two main regimes: (i) the first is measured during fall and winter (the wet period of the year) where the SR values are close to 1 and they can be considered as "non-relevant" for PV plants operation. (ii) The second regime is detected during the dry period of the year (spring and summer) where the SR values start decreasing until achieving a minimum value in August. Indeed, for CdTe, 0.75 was its lowest value recorded in the middle of August, while it was around 0.72 for the poly-Si technology.

In the current study, our focus is directed to understand the soiling's impact on the modules temperature as it contributes to the partial shading, therefore, the creation of hot spots and temperature increase. Given the fact that soiling is more significant during the dry period which is also linked to high-temperature values, we will focus only on this period to find any possible correlation between the SR and the increase of the module's temperature. However, before that and for better analyze the SR behavior during this period, the frequency distribution of the parameter -From 01/June to 03/September-is calculated for both technologies and presented in Figure 7a and 7b.

As it can be observed, the most frequent values related to the dry period are the one in the range between 0.8 and 0.85 (for both technologies) with an occurrence of around 40% for CdTe and around 35% for poly-Si. In addition to that, it has been observed that the Poly-Si is highly affected by soiling where 5% of the measured data are ranging in the interval between [0.75–0.7], while this interval includes no measurement for the CdTe technology.

In the next section we will present the results of the soiling impact on electricity production and the efficiency of both technologies. Besides, we will focus on finding the relation between the SR and the modules' temperature.

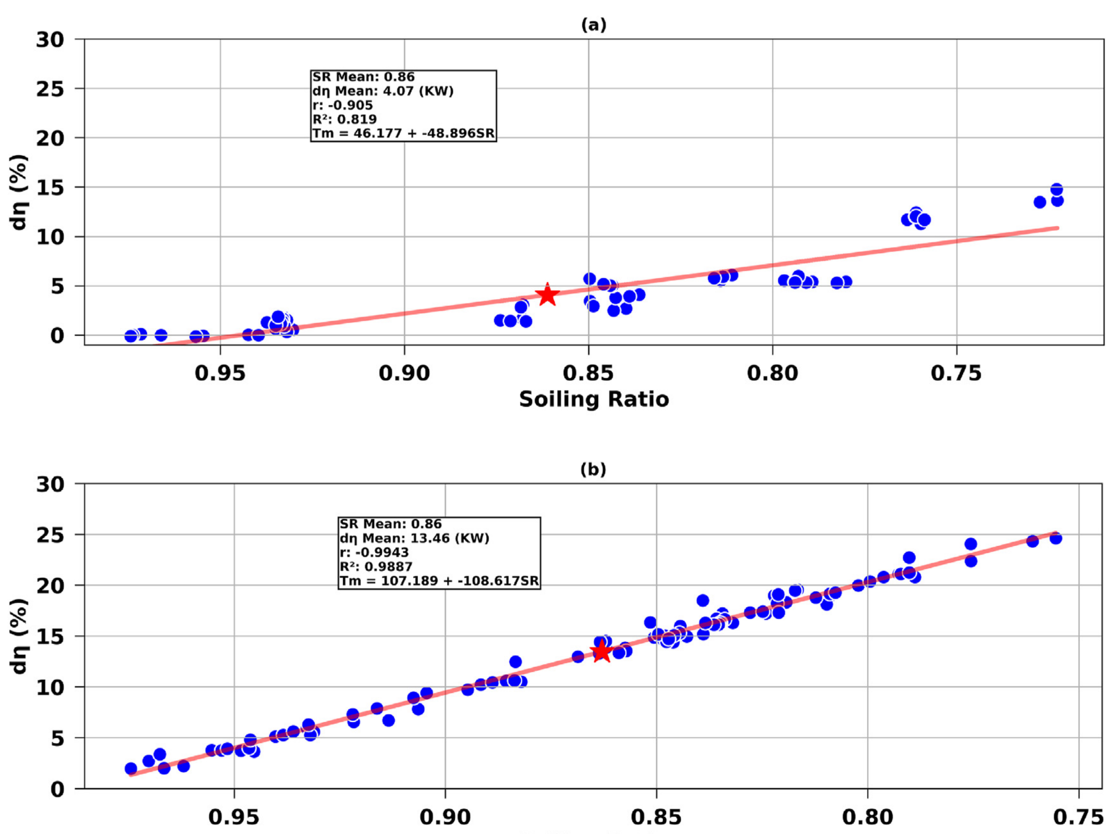

Figure 9. Correlation between efficiency deviations and soiling ratio for both technologies: (a) poly Si technology, (b) CdTe technology. d) Effect of soiling on the modules temperature.

2.3. Soiling impact on the PV production

As discussed previously, the impact of the SR values on PV modules was considerable during the dry period of the year, that's why in the results section we will focus only on this period of the measurement campaign to assess the drop in the modules yield due to soiling.

One of the most common used metric to report the yield of PV modules is the Specific yield, especially while comparing different technologies/configurations with different nominal capacities. This metric represents the amount of energy (kWh) produced per kWp of the module capacity over a period of time.

In the current investigation, we will evaluate the soiling effect on both technologies by calculating the daily deviation (dY_r) of the specific yield between the clean and the soiled modules from each technology using Eq. (2):

$$dY_r = \frac{Y_s^{clean} - Y_s^{soiled}}{Y_s^{clean}} \tag{2}$$

where

dY_r is the daily specific yield relative deviation between soiled and clean panels.

Y_s^{clean} is the specific yield of the clean panel in (kWh/kWp).

Y_s^{soiled} is the specific yield of the soiled panel in (kWh/kWp).

Figure 8 presents the deviation in the specific yield for both inspected technologies. As it can be noticed, the specific yield deviation -in other words, a drop on the production-reveals a significant increase during the dry period of the year, where the daily deviation in the specific yield (between the clean and the soiled modules) can reach 35% for the Poly-Si and 25% CdTe technology.

We need to mention that this deviation starts decreasing to reach 2% at the end of the dry period with the presence of rainfall event in September that cleaned the soiled modules.

In terms of technologies, Poly-Si is more affected by dust than CdTe. This is completely logical since the materials of the two technologies have different physical properties. In fact, the CdTe, has a higher band gap in comparison to the PolySi, consequently, a less temperature impact on the power production due to the low temperature coefficient.

Besides, the cells of the Poly-Si modules are not uniform in temperature, consequently, the higher the temperature is the more the non-uniformity will be. This fact is highly manifested when soiling is deposited on the modules surface causing a partial shading on the cells of the PolySi, and leading to a higher drop on the production in comparison to the CdTe.

For a better evaluation of the soiling on the performances of the PV technologies, a correlation between the SR and the modules' efficiency deviation ($d\eta$) (between the clean and the soiled one) has been plotted in Figure 9.

The efficiency of the modules is calculated using Eq. (3):

$$\eta = \frac{P}{A^*G}{}^*100 \tag{3}$$

where P (W) is the power of the PV module, A is the panel area (m^2) and G is the plan of array irradiance (W/m^2).

In addition the efficiency deviation is calculated using Eq. (4):

$$d\eta = \eta_{clean} - \eta_{soiled}(\%) \tag{4}$$

Based on Figure 9, it can be noticed that $d\eta$ between the clean and the soiled PV modules is increasing while the SR increases for both technologies. For the CdTe, a good agreement between the $d\eta$ and the SR is observed with an $R^2 = 98.8\%$, besides, the maximum deviation of the module efficiency is around 25% and this value has been recorded for SR values around 0.75.

As for the Poly-Si technology, the correlation between the $d\eta$ and the SR is also considered as good with an $R^2 = 82\%$. Nevertheless, the drop on the efficiency due to soiling is less than the one for CdTe even for higher SR values. In fact, as it can be noticed from the figure, for a SR around 0.72, the efficiency deviation is of 15%. This can be explained by the sensibility of this technology to the ambient temperature (especially for the clean module) which decreases its efficiency, causing a drop in the efficiency difference between the clean and the soiled one. In the next section, we will focus on the impact of the soiling ratio on the temperature on the PV modules.

To assess the soiling impact on the modules' temperature, the daily averages of the module temperatures measurements over the dry period are measured and plotted against the SR values in Figure 10. As it can be noticed, for both technologies, the temperature of the soiled modules keeps increasing with the increase the dust accumulation. We should mention that for the calculation of the T_m daily averages, we used the values between 9:00 AM and 6:00 PM in order to include the values in accordance with the real operation of the PV modules.

We should mention that the T_m values are affected by the irradiance and the ambient temperature, however, in our case these parameters are not considered since the investigated PV modules: (i) are similar (by technology), (ii) exposed side by side and at the same location, also (iii) they operate under the same conditions i. e they receive the same irradiance and they are merged at the same ambiance with the same temperature values. Therefore, we can consider that the difference in the T_m values is directly linked to the amount of soiling deposition on the modules surface.

For more details, the daily modules' temperatures together with their deviations are plotted in Figure 11. As it can be noticed, during the dry period the modules' temperatures are generally higher than 35 °C. In addition, the modules' temperature can reach 50 °C. The temperature

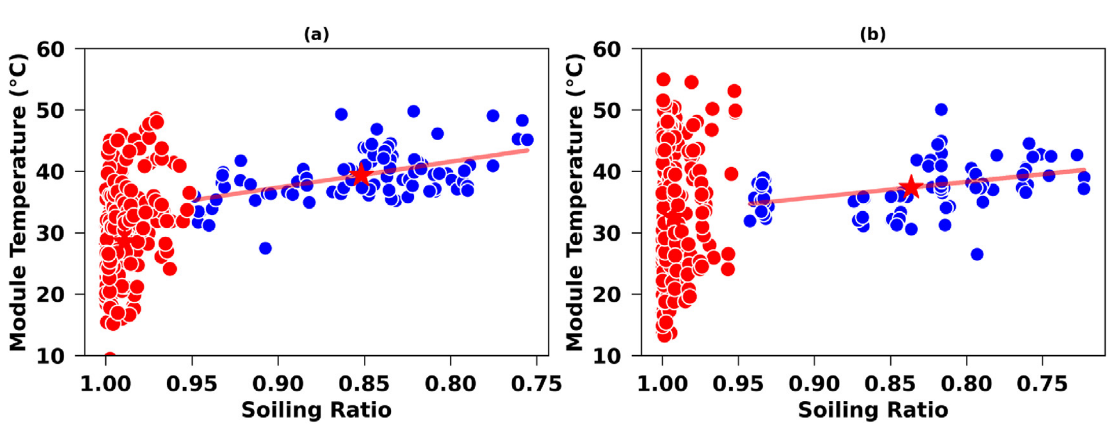

Figure 10. Correlation between the SR and the modules temperature: (a) CdTe technology, (b) poly-Si technology.

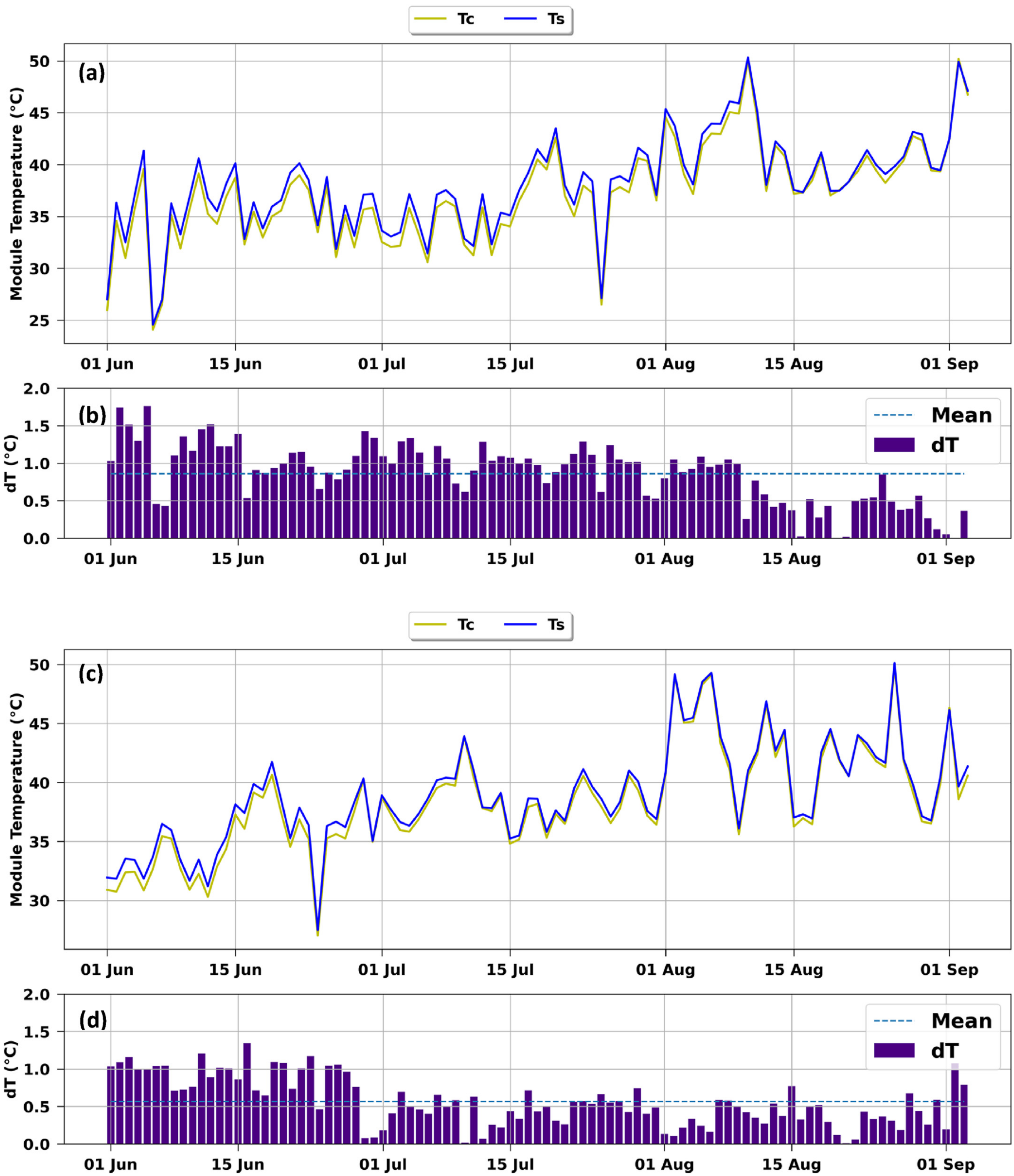

Figure 11. Soiling impact on the modules temperature. (a) Daily temperatures variations of the Clean and the Soiled modules together for the Poly-Si technology (b) the modules temperature deviation for the Poly-Si technology (c) Daily temperatures variations of the Clean and the Soiled modules together for the CdTe technology (b) the modules temperature deviation for the CdTe technology.

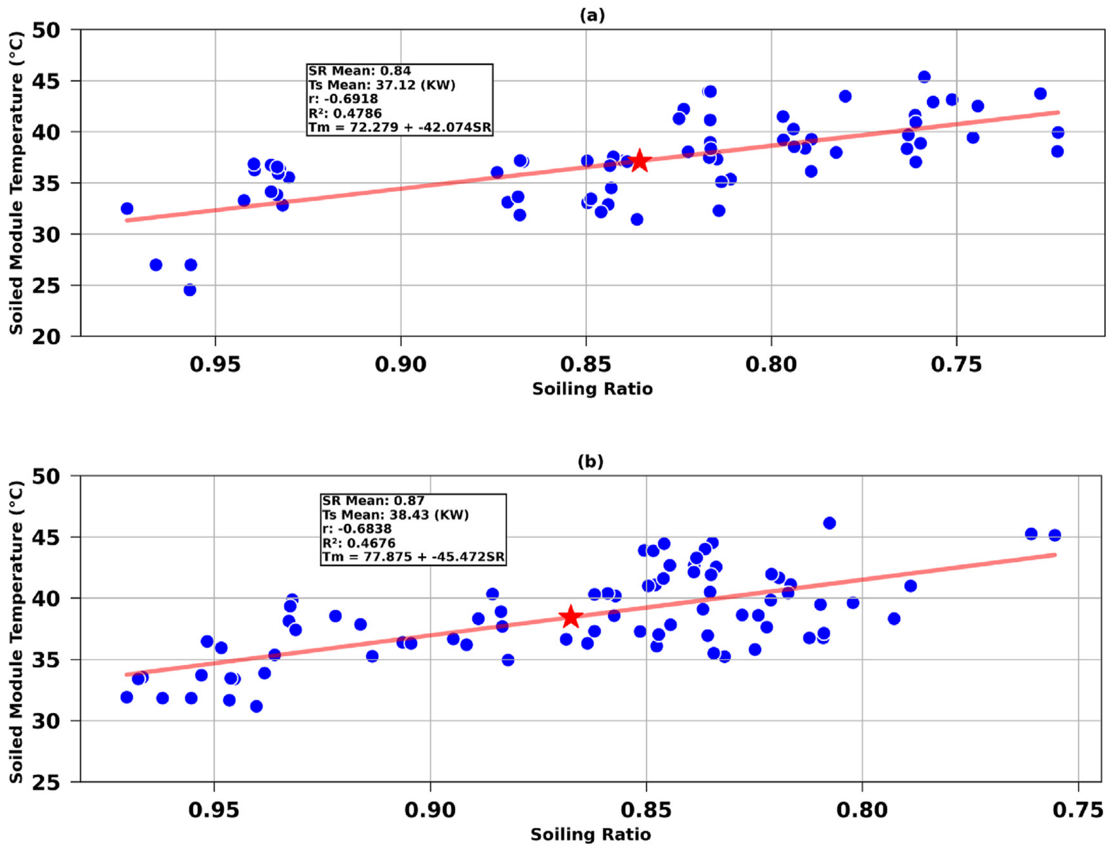

Figure 12. Soiled module temperature as a function of soiling ratio for (a): poly-Si and (b): CdTe technologies.

deviations (dT), between the clean and the soiled modules, allow us to clearly observe the impact of soiling on the module temperature. In fact, the daily dT can reach 1.8 °C for the Poly-Si technology, while it barely reaches 1.3 °C for CdTe. The mean daily temperature deviation -between the clean and the soiled modules-during the dry period is of 0.8 °C and 0.6 °C for Poly-Si and CdTe respectively.

Back to the objective of this section, to evaluate the direct impact of soiling on the modules' temperature a correlation between the daily Tm and SR has been conducted, see Figure 12. As it can be noticed, for SR values ranging between [1 and 0.95], the module's temperature has a trend to vary (along the range between 20 and 50 °C) with no accordance with the SR. Nevertheless, with the high soiling deposition (SR values less than 0.95) a linear fitting appears presenting the correlation between the SR and the Tm.

Indeed for the first interval SR $>$ 0.95, the modules -from both technologies-are considered as “Clean”, thus the Tm is not yet affected by this parameter and it is only related to the other factors like higher temperatures values and the high POA recorded during this selected period.

However, for SR $<$ 0.95 more dust is accumulated on the modules' surface creating some shading on the cells, therefore, a leakage current-conducting to an increase in the modules’ temperature. In this SR regime, a linear relationship can be observed between the Tm and the SR for both technologies where the Tm increases with low SR values with a correlation coefficient R^2 of 46.7% and 47.8% for the CdTe and the Poly-Si respectively.

For a better understanding of the impact of the dust accumulation on the Tm, the Cumulative soiling rate index (CSRI) has been proposed. This metric represents the soiling state (SR) of the PV modules after an exposition period in comparison to the SR state of the first exposition day. The idea of introducing this metric is to predict the increase in the Tm value for a specific PV technology based on the SR value after a specific period. The CSRI is calculated as in Eq. (5) and it is presented in the following sections.

$$CSRI(i) = SR(i) - SR(1) \tag{5}$$

where SR(i) is the calculated soiling ratio for the ith day and SR(1) represents the soiling ratio on the first day.

Figure 13 shows the correlation between the proposed CSRI for the experimental period and the Tm for the soiled CdTe and poly-Si modules. As it can be observed, for both technology, the two parameters have a linear relationship where the Tm increases while the CSRI increases. The poly-Si provides a good agreement/linearity between the two parameters (Tm and CSRI) in comparison to the CdTe with an R^2 = 48.2% against 47.4%.

To wrap up, using the proposed CSRI metric the one can predict the impact of the soiling on the module's temperature using the linear equations bellow:

- For Poly-Si technology: $T_m = 59.96 * CSRI + 29.6$
- For the CdTe technology: $T_m = 48.9 * CSRI + 33.8$

This equations can lead to a better evaluation of the modules efficiency if installed on desert locations by including the module's temperature as well as the impact of dust deposition on this last. Nevertheless, we need mention that the above equations represent only a preliminary semi-empirical model aiming to find a direct link between the T_m and SR values and it should be tested in other locations for a better validation.

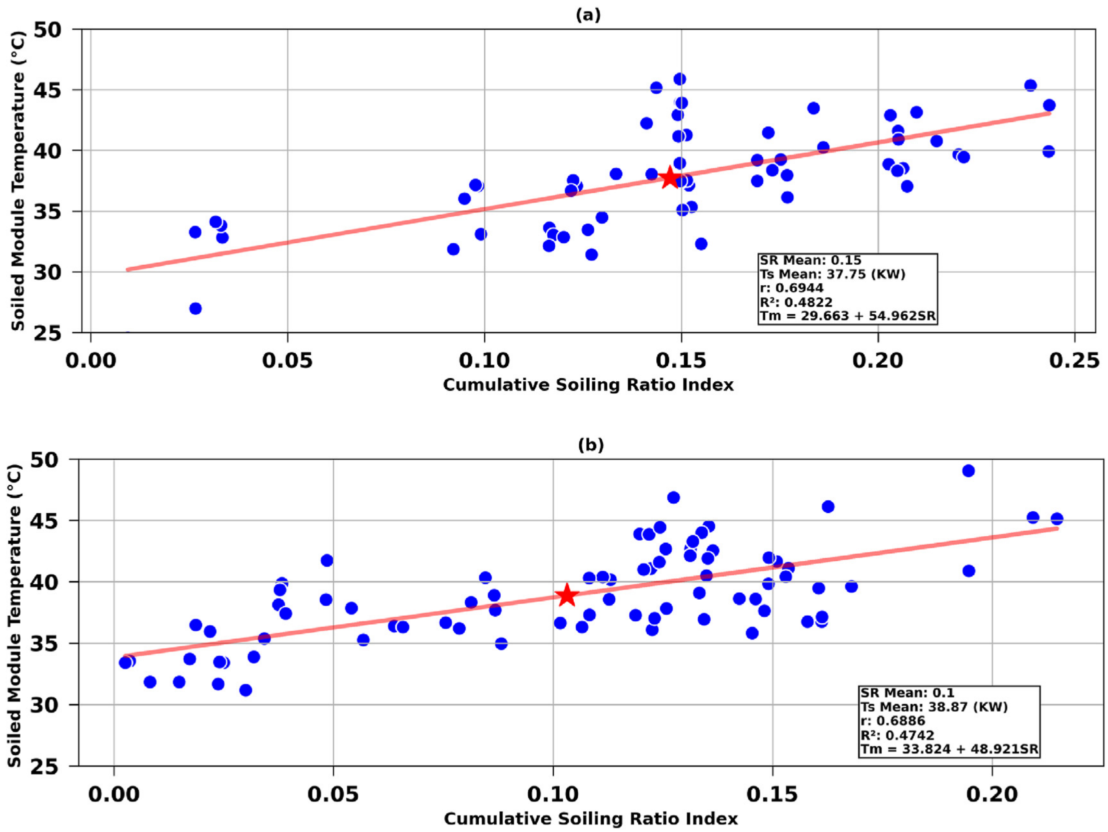

Figure 13. Temperature of the soiled module as a function of cumulative soiling rate (a): poly-Si technology and (b): CdTe technology.

3. Conclusions

In this paper we assessed the soiling impact on the modules temperature and the performances of two different PV technologies. To do so, we conducted a one year experiment where two modules form each technology were exposed in outdoor conditions under a semi-arid climate. For each technology, one of the modules was cleaned every day while the other was left without cleaning to accumulate the dust and soiling on its surface.

From the experimental protocol, we firstly measured the daily Soiling Ratio (SR) for both PV technologies, after that, we evaluated the SR impact on the electricity production. In addition the relation between the SR and the increase on the module's temperature has been studied and based on the SR measurements we proposed a model to predict the impact of dust deposition on the modules temperature. The main results of this study are summed in what follows:

- For our field of study soiling is a big problem especially during the dry period of the year where the SR can reach 0.7 for the Poly-Si technology and 0.75 for the CdTe.
- Poly-Si modules are highly affected by Soiling than the CdTe technology.
- The daily drop in the energy of the Poly-Si technology can reach 15% and it is around 13% for the CdTe.
- For both technologies a good agreement has been observed between the SR and the Tm values for high deposition events (SR < 0.95) with an $R^2 = 46.7\%$ for the CdTe and 47.8% the Poly-Si.
- The module temperature from the Poly-Si technology is more affected by Soiling than the CdTe one, due to the property of this technology characterized by a high bandgap leading to a better temperature coefficient of the module.

Declarations

Author contribution statement

Nabil AMMARI, Maryam MEHDI, Ahmed ALAMI MERROUNI: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Hicham EL GALLASSI, Elmiloud CHAABELASRI, Abdellatif GHENNIOUI: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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