# Impact of soiling on the outdoor performance of CPV modules in Spain

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# Impact of Soiling on the Outdoor Performance of CPV Modules in Spain

Jesús Montes-Romero[1,a)], Leonardo Micheli[1], Marios Theristis[2], Álvaro Fernández-Solas[1], Juan de la Casa[1], George E. Georghiou[2], Florencia Almonacid[1] and Eduardo F. Fernández[1]

[1]*Centro de Estudios Avznados en Energía y Medio Ambiente (CEAEMA), University of Jaén, Las Lagunillas Campus, Jaén 23071, Spain*
[2]*PV Technology Laboratory, FOSS Research Centre for Sustainable Energy, University of Cyprus, Nicosia 1678, Cyprus*

[a)]Corresponding author: jmontes@ujaen.es

**Abstract.** This paper presents an experimental study on the effect of soiling on CPV modules located in the south of Spain. The I-V curves of two identical modules with different cleaning schedules (i.e. one was naturally soiled and the other one was cleaned periodically) have been measured over a course of year. The effect of soiling on the short-circuit current, maximum power and fill factor are presented together with the rain accumulation and particulate matter concentrations. Results showed that no losses occurred during the rainy periods, whereas for dry periods, a significant decrease in performance was observed due to soiling. Soiling was also found to have a greater influence on the maximum power rather than the short-circuit current. The highest power drop of up to 19% was measured after two dry summer months. Overall, the annual energy loss due to soiling was found to be 5.7%.

## INTRODUCTION

The accumulation of dust, dirt and particles on the surface of PV and CPV modules is an issue, known as soiling, that affects systems worldwide, causing significant energy and hence, revenue losses [1]–[3]. High irradiance regions such as the MENA countries and India are particularly profitable for CPV [4], but can, at the same time, be exposed to extreme soiling, because of the dry and sandy soil, the long seasons without rainfalls, the high concentrations of particulate matter and/or a combination of these and other factors [5].

A large number of scientific studies investigates the effect of soiling on flat PV devices, but the number of investigations focused on soiling of CPV systems are scarce. Due to the special and more complex characteristics of CPV systems, the correlations and the results of the studies on soiling of flat PV devices are not necessarily valid for CPV. In the case of flat PV devices, indeed, soiling mainly reduces the intensity of the light transmitted through the glass to the solar cell, whereas for CPV systems, other effects such as the light scattered out of the acceptance angle, critical mismatch problems due to non-uniform soiling [6], and changes in the spectral irradiance are also present [7]. Therefore, soiling on CPV systems is expected to impact the spectral mismatch ratio as well as the I-V characteristics.

The purpose of this paper is to present an experimental study of the soiling effect over CPV modules and the influence of rain on its performance. An annual and a seasonal study has been carried to evaluate the electrical performance of a soiled and a clean module, and to analyze how the rainy and dry periods affects the CPV behavior in a high irradiance location.

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# MATERIALS AND METHODS

The experimental setup is located at the University of Jaen, in the South of Spain. This area is non-industrialized with low to medium values of precipitable water and aerosol content. The annual global solar irradiation is usually greater than 2000 kWh/m2 and the annual direct normal irradiation is around 1800 kWh/m$^2$. The ambient temperature ranges from approximately 5°C in winter to 40°C in summer.

Two identical 500× CPV modules have been mounted on a two-axis tracker (Fig. 1). The primary optics of these modules are made from Silicon-on-glass (SoG) with no anti-reflective coating (ARC) and with a lens area of 571cm$^2$. Six series-connected lattice-matched GaInP/GaInAs/Ge solar cells convert the concentrated light beam into electricity. One of the two modules is cleaned once a week (reference module), while the second is left to soil naturally (soiled module). Meteorological sensors are also cleaned weekly. The reference module is cleaned with a wet cloth, while the sensors are cleaned with a dry cloth. The I-V curve, direct normal irradiance, spectral characteristics and temperatures of the two CPV modules and lenses have been collected at a 5-minute interval. In addition, other relevant parameters to soiling such as rain accumulation, in mm/day, and particulate matter, expressed as $PM_{10}$ concentration in µg/m3, have been constantly measured. The rainfall data have been collected from the "Matras" meteorological station of the Physics Department of the University of Jaen [8], and the PM10 concentration has been obtained from the "Junta de Andalucia" database, with a meteorological station located at "Ronda del Valle" [9], close to the University of Jaen.

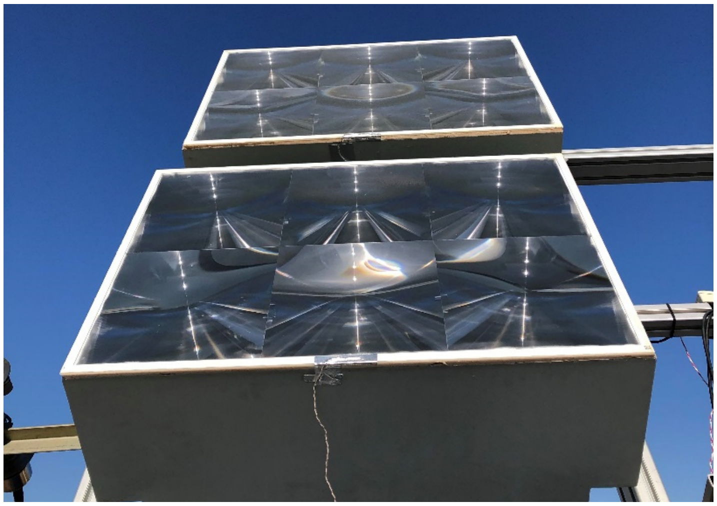


**FIGURE 1.** The two CPV modules mounted in Jaen, southern Spain, and used in this investigation. The top module is soiled and the bottom module is clean and used as reference.

Soiling is quantified through the soiling ratio, calculated as the ratio between the electrical output of the soiled module to the electrical output of the reference module. This metric, defined in [10], has a value of 1 if the soiled module is clean and decreases while soiling is accumulating on the soiled module's surface. The soiling losses can be estimated as the difference between 1 and the soiling ratio, in %. For example, a soiling ratio of 0.9 corresponds to a soiling loss of 10%. In this study, no irradiance weighting is performed in the calculation of the soiling ratio.

The soiling ratio in this study has been calculated by considering various electrical parameters: short-circuit current ($I_{SC}$), open-circuit voltage ($V_{OC}$), maximum power ($P_M$) and fill factor (FF). The initial soiling ratios has been measured on the first day of the experiment and an offset correction has been included to normalize the differences between both CPV modules for each electrical parameter. These values have been corrected to Concentrator Standard Test Conditions following the process described in [11]. In this sense, equations (1), (2) and (3) are used:

$$I_{SC}^{*} = I_{SC}\frac{DNI^{*}}{DNI}\left[1-\delta_{I_{SC}}(T_c-T_c^{*})\right] \tag{1}$$

$$V_{OC}^{*} = V_{OC}-\mathrm{N}_s\cdot m\cdot V_T\cdot\ln\frac{DNI}{DNI^{*}}\left[1-\delta_{V_{OC}}(T_c-T_c^{*})\right] \tag{2}$$

$$P_M^* = P_M \frac{DNI^*}{DNI}\left[1 - \delta_{P_M}(T_c - T_c^*)\right] \quad (3)$$

where * indicates the reference conditions, $\delta_{I_{SC}}$, $\delta_{V_{OC}}$ and $\delta_{P_M}$ are the temperature coefficients for each electrical parameter, $m$ is the diode ideality factor and $V_T$ is the thermal voltage calculated as k·T/q, being k the Boltzmann constant with a value of 1.38E-23 J/K and q the electron or elementary charge with a value of 1.60E-19 C. The FF is calculated as the ratio between $P_M^*$ and the product of $I_{SC}^*$ and $V_{OC}^*$.

## RESULTS

To carry out this study, the values of the three electrical parameters described in equations 1, 2 and 3 recorded from April 2017 to October 2018 have been considered in order to cover a full year of outdoor exposure. In order to reduce the scattering effect and delete wrong data, several data filters have been applied, as recommended by the standards [12]: DNI variations during I-V sweep of more than 1%, Fill Factor values outside the range of 60-100%, DNI variations of 10% in 10 minutes periods, DNI variations of 40% in 30 minutes periods, DNI values lower than 700 W/m$^2$ and SMR outside 1 ± 0.05. A daily soiling ratio for each of those parameters has been calculated as the average value for a complete day. The daily soiling ratio for the power at maximum power point and the accumulated daily rain are shown in FIGURE 2. The vertical blue lines in Fig. 2 represent the accumulated daily rain and help to distinguish between dry and rainy periods. Clearly, a seasonality in soiling ratio is observed from the figure. Specifically, during dry periods, soiling deposits on the modules' surface and affects the PV generation, and the soiling ratio tends to decrease over time. During rainy periods, instead, the soiling ratio remains close to one. A first dry period can be seen starting in September 2017, where the soiling ratio decreased by 0.05 until a rainy day in November, where the soiling ratio goes back to 1. From this rainy day, a long rainy period maintains the soling ratio close to 1. A "new" dry period began in June 2018 resulting to a clear soiling loss; i.e. the soiling ratio decreases by 0.2 in two months. Furthermore, more data spreading can be seen for rainy periods due to the presence of clouds that affect the stability of measurements, in contrast with the dry periods, where the measurements tend to be more stable.

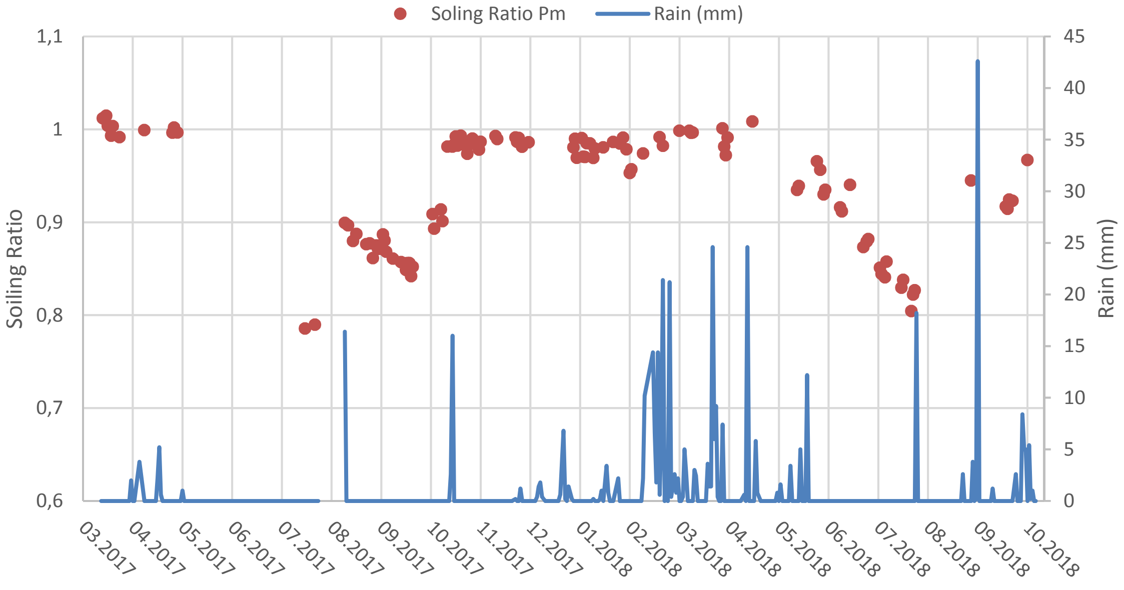


**FIGURE 2.** The daily average soiling ratios calculated by comparing the maximum power outputs of the two modules. The vertical blue lines mark the rainy days. No soiling ratio and electrical data were recorded in between 06/2017 and 08/2017.

Annual losses caused by soiling have been studied over the investigated data collection period. In Table 1, the annual average values of accumulated rain, PM$_{10}$ concentrations, and soiling ratios for V$_{OC}$, I$_{SC}$, P$_M$ and fill factor (FF) are presented. These values are estimated as the average of the 5-minutes interval data set with the before mentioned filters. Approximately, 20,000 data points of measured soiling ratios were used. An annual average loss in power of 5.7% was measured, whereas, for short-circuit current, the loss was 4.6%. The V$_{OC}$ soiling ratio presents an annual average value of 1.01, which indicates an ineligible effect of soiling on voltage. The current and power drops due to soiling influence the FF with an annual reduction of 1.9%. This indicates that soiling produces non-negligible mismatch effects among the receivers that further enhance the soiling power losses. Rain (expressed as accumulated rainfall) and PM, which are the main meteorological and atmospheric parameters influencing soiling [13], were 47.05 mm/month and 23.27 μg/m$^3$/day on average. The presented values report the 95% of the confidence interval [14], [15].

**TABLE 1.** Annual average values and standard deviation of rain, $PM_{10}$ and Soiling Ratios of $V_{OC}$, $I_{SC}$, $P_M$ and FF.

| Parameter | Annual average value | Standard Deviation |
|---|---|---|
| Rain (mm) | 47.05 | 2.14 |
| $PM_{10}$ (μg/m$^3$) | 23.27 | 16.57 |
| Soiling Ratio $V_{OC}$ | 1.009 | 0.037 |
| Soiling Ratio $I_{SC}$ | 0.954 | 0.075 |
| Soiling Ratio $P_M$ | 0.943 | 0.095 |
| Soiling Ratio FF | 0.981 | 0.065 |

As discussed earlier, soiling exhibits seasonality over the course of a year, being more severe during the longest dry periods. In order to study its seasonality, the monthly average values of soiling ratio have been calculated. In this sense, monthly accumulated rain in mm, monthly average $PM_{10}$ in μg/m$^3$ and monthly average soiling ratios of $P_M$ and $I_{SC}$ are presented in Fig. 3. During the experimental period, monthly accumulated rain variations from 27mm (February 2018) to 55mm (April 2018) per month were experienced in most of the cases. An especially rainy month occurred on March 2018 with an accumulated rain of 205.4 mm, and soiling ratios very close to 1. As it can be seen in Fig. 3, the soiling ratio achieve the lowest values (i.e. the soiling losses increase) during the driest periods of the year (September 2017 and July 2018).

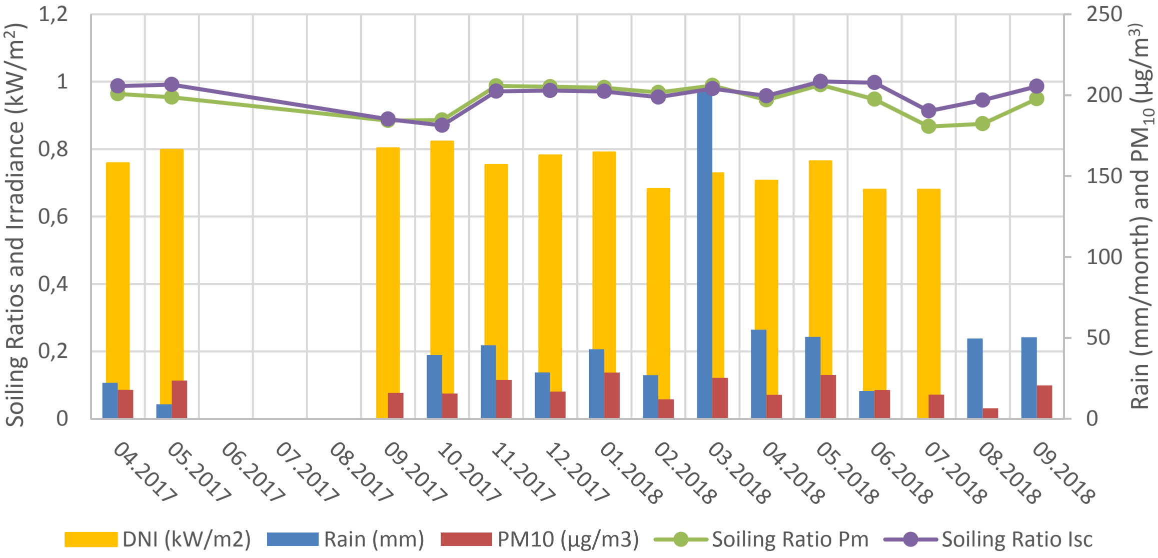
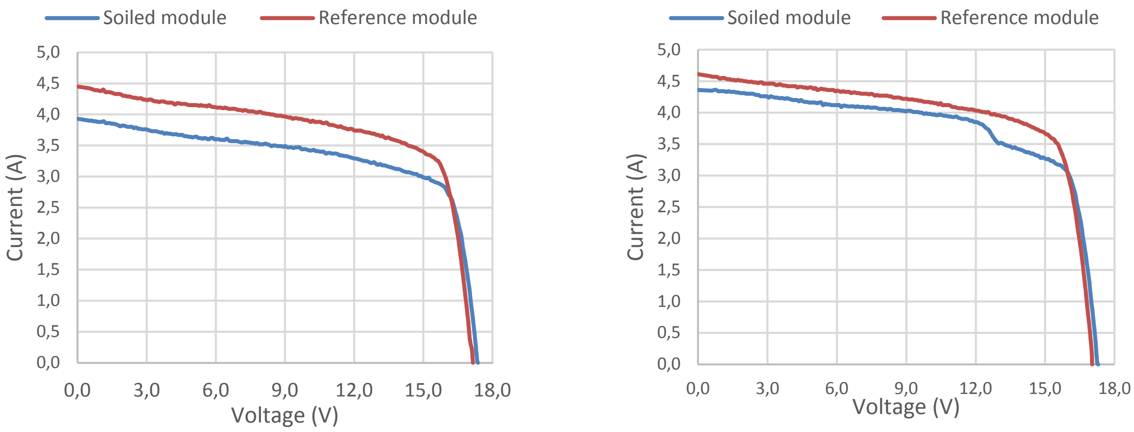


**FIGURE 3.** The monthly average values of soiling ratio of maximum power, soiling ratio of short-circuit current and average DNI (left y-axis), monthly average $PM_{10}$ and total monthly rain (right y-axis).

During rainy periods, the soiling ratios of $P_M$ and $I_{SC}$ maintain values close to 1 and follow the same seasonal trends. It can also be noticed that $P_M$ value is slightly higher than $I_{SC}$ during rainy seasons. This can be due to the inherent tolerance of electrical parameters among different CPV modules and misalignment. The difference between the two ratios becomes noticeable from June 2018, when the rainfall events are limited and the dry periods become longer and more frequent. A maximum difference of 0.07 can be found between the soiling ratios based on maximum power and short-circuit current on August 2018. Soiling clearly affects more the power generation than the current. If a linear fit is applied to this dry period –July to August 2018–, the $P_M$ soiling ratio is found to decrease by 0.31%/day while the $I_{SC}$ soiling ratio decreases by 0.26%/day.

The difference between $I_{SC}$ and $P_M$ soiling ratios and, therefore, the decrease of fill factor is due to the non-uniformity of soiling which produces a mismatch effect among the cells of the soiled modules. In order to illustrate this effect, the I-V curves from different periods with similar $P_M$ soiling ratios are shown in Fig. 4. The curves were taken at noon during days with irradiance levels over 700 W/m$^2$. The cell temperature is calculated from the module temperature, which is measured on the back plate of the module. It has been calculated considering the thermal resistance and characteristics of the module as described in [16], [17]. As can be seen in Fig. 4(a), both I-V curves follow the same trend; i.e. the soiled module presents a uniform soiling distribution. The $P_M$ and $I_{SC}$ soiling ratios were 0.88 and 0.89 respectively during that day. The curves in Fig. 4(b) were obtained on the 1st of September 2018 exhibiting a $P_M$ soiling ratio of 0.90 against an $I_{SC}$ soiling ratio of 0.94; this difference indicates a non-uniform soiling issue. In addition, while the reference module did not present any mismatch on current generation, a mismatch step affected significantly the fill factor of the soiled module. This problem persisted until the next rainfall event on the 8th of September. In terms of the fill factor under uniform and non-uniform soiling conditions, the uniform soiling produced a 0.99 FF soiling ratio, while the non-uniform presented a 0.93 FF soiling ratio.



(a)

(b)

**FIGURE 4.** Examples of I-V curves of soiled and reference module from days with uniform and non-uniform soiling: a) Soiling Ratio ($P_M$) of 0.88 at 799W/m$^2$, cell temperatures of 67ºC and 72ºC for soiled and reference modules temperature respectively, for a day with high-uniform soiling; b) Soiling Ratio ($P_M$) of 0.90 at 832 W/m$^2$ on a day with highly non-uniform soiling. Measured module temperatures of 64ºC and 67ºC for the soiled and the reference module respectively.

## CONCLUSIONS AND FUTURE WORKS

A year of data from two identical CPV modules have been analyzed in order to study the influence of soiling, taking into account the effect of rainfall.

The annual study shows that for an average 47.05 mm of rain and 23.27 µg/m$^3$ of $PM_{10}$, the soiling ratio of $V_{OC}$ does not present any losses, while the $I_{SC}$, $P_M$ and FF exhibit loses of 4.6%, 5.7% and 1.9% respectively. It can also be noted that soiling affects the maximum power value to a greater extend compared to the short-circuit current. A seasonality study showed that, as expected, the performance of the CPV modules degrades during the long, high irradiance and dry summers, with a minimum soiling ratio of 0.81 (i.e. a power loss of 19%), whereas losses are limited during the rainy periods.

Mismatch problems were found during highly soiled periods in presence of non-uniform soiling. This effect explains the difference between current and power soiling ratios occurred in summer 2018, with a maximum difference of 7% between the loss in maximum power and the loss in short-circuit current. Future work will include studying the impact of soiling on temperature and spectral variations in relationship with parameters such as rainfall and particulate matter. It is expected that the main soiling impact on temperature is the reduction of irradiance to the cell, which causes a decrease on the temperature of the module. The non-uniform soiling may produce mismatch effect problems among the receivers, generating hot spots issues. For spectral influence, the soiling tends to decrease mostly the blue part of the spectrum. This effect may lead to a mismatch effect between the top and middle subcells, reducing the output of the module and increasing the temperature of the cell.

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