EVALUATION OF THE SELF-CLEANING EFFECT ON THE PERFORMANCE OF PV PLANTS

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ABSTRACT: Seasonal rain can clean PV panels from dirt and droppings that may have accumulated over time. Therefore, PV installations in regions where rainfall is frequent do not necessarily need mechanical cleaning in order to optimize the financial yield of the PV system. In the present work, the effect of rain events on the performance of several PV plants in Switzerland is evaluated. Collected energy yield data is analyzed and used to calculate the performance ratio (PR) of the investigated PV systems. The PR is calculated before and after various precipitation events. The self-cleaning mechanism is correlated to the intensity of precipitation events. It has been shown that light precipitation can accelerate the soiling of PV modules, while heavy precipitation cleans the modules.. In this paper, a threshold for effective rainfall is calculated and the frequency of such events in the investigated locations is given. It could be shown that for the systems under investigation, precipitation events until 15 mm per day increase soiling, whereas precipitation events above 15 mm clean the modules. However, the uncertainty of these values is big.
Keywords: Self-cleaning, yield, performance ratio

1 INTRODUCTION

Different parameters can affect the PV system performance in a negative or a positive way. This depends among others on the tilt angle of the modules and on the conditions to which these parameters contribute [1]. Hence, rainfall is one of these factors, it has a positive impact on the PV performance when rain is heavy, which is equivalent to a cleaning event. Otherwise, it can be a soiling factor when the precipitations are slight, and therefore the water droplets will lead to a decrease in the PV system performance. Recently, E. Simsek et al. [2] experimentally investigated the impact of dew or rain droplets on the performance of PV cells as a function of the tilt angle. Found results indicated that the droplets negatively affect the efficiency of PV cells when the tilt angle is higher than 30° depending on the size of the droplet. A. Gopi et al. [3] analyzed the performance of a PV plant under a humid tropical climate dominated by monsoon seasons. It was found that during the monsoon seasons, rain affects the annual energy generation, which decreased by 36%.

In another work, A. Gopi [4] modeled the influence of different weather parameters on the performance of this PV plant. From obtained results, the performance ratio of the PV plant is higher during the rainy periods because of the PV temperature drops. The impact of rain on the performance of PV or on the state of the PV module surface is a complex issue, especially when other weather parameters affect the properties of the module surface. Jia Yun Hee et al. [5] highlighted that the transmission through plain PV glass decreased from 90.7% to 87.6% after one month of outdoor exposure. However, rain has strong impact on removing the amount of accumulated dust on the surface when wind is also present. Moheyer, M. Gerardo, et al. [6] studied the impact of rainfall on the performance of 60 kWp PV system for one week. After the rainy event, the energy generation increased from 63.6 % to 77.3 % and from 76.6 % to 76.8 % for the PR. P. Wang et al [7] studied the effect of superhydrophobic thin film on anti-reflection and self-cleaning of the PV module. Dust deposition and rainfall were artificially investigated on coated and uncoated samples. From found results, the proposed coating leads to an increase of light transmittance, short-circuit current and output power of 2 %, 17.1 % and 15.7 % compared to uncoated modules, respectively.

Furthermore, several thresholds of rain events are reported in literature as well as the cleaning impact of the rainfall events on soiling. Kimber, Adrianne, et al. [8] indicated that an amount of rainfall of 20 mm could clean the studied PV system, which lead to an efficiency increase of 40 %. It is also mentioned that there is no exact and clear threshold for cleaning. The relevant rain amounts are presented according to each system. Formerly, Hammond, R., et al. [9] analyzed the effect of rain and tilt angle on PV module soiling. As a result, the modules retrieved 1 % of power when it is rainy, and 5 mm of rain could reduce the soiling losses up to 0.5 %. W. Javed et al. [10] found from their analysis study on PV soiling that a minimum rain amount of 3 mm could fully clean 3.5 kWp PV modules, while rainfall less than 2 mm partially cleaned the modules. Moreover, L. Micheli et al. [11] used historical weather data to optimize the cleaning schedule of 1 MW PV site. The optimization is based in soiling prediction using rainfall and cleaning threshold values.

2 GENERAL DESCRIPTION OF THE PV SYSTEMS

In this study, the self-cleaning effect of three PV systems in Switzerland was analyzed. The first system called “Tiergarten” is installed on the rooftop of Bern University of Applied Sciences in Burgdorf, Bern. It is divided into two sub-systems, namely Tiergarten West and Tiergarten East with a nominal power of 24 kWp and 22 kWp, respectively.

The other investigated PV system is Mont-Soleil with a total nominal power of 555 kWp, and it is located in Jura. Both regions are characterized by warm-temperate climate according to Köppen classification [12]. The amount of annual precipitation is 1174 mm and 1619 mm in Burgdorf and Jura, respectively.

3 METHODOLOGY

3.1 Analysis of long-term data series

This approach is a preliminary step to carry out the study. It consists of the preparation and analysis of 1 min data series, and standard performance metrics are calculated using the measured parameters. More than 20 years of recorded and measured data of different weather and PV system parameters are explored in this study. For the data preprocessing and the calculation of proposed performance standard metrics, MATLAB software is used. Performance ratio (PR) is the most crucial standard used worldwide for the assessment of the performance of the PV plant. It is defined as the ratio between the DC yield (final yield) and the reference yield [13]:

$$PR=\frac{Y_{DC}}{Y_r} \quad \text{(Equ.1)}$$

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The DC yield is defined by total DC energy output produced (E_{DC}) by the system divided by the nominal power of the PV system at STC (P_{nom}) [14]:

$$Y_{DC} = \frac{E_{DC}}{P_{nom}} \times k_T \quad \text{(Equ.2)}$$

k_T is the temperature correction factor and it is presented as:

$$k_T = 1+\alpha_{Pmpp}\times(T_{ref}-25) \quad \text{(Equ.3)}$$

Where T_{ref} is the solar generator cell temperature and α_{Pmpp} is the temperature coefficient (%/°C).

The reference yield is the ratio of the total tilted solar irradiance (GTI) to the refence solar irradiance (G_{STC}) [15], and it is expressed as:

$$Y_r = \frac{GTI}{G_{STC}} \quad \text{(Equ.4)}$$

3.2 Modeling the impact of rain events on the PR

To model and determine the impact of rain events on the PR of PV systems, a PR gain metric (PR_g) is proposed. In this approach, correlation between the PR and rain intensity is studied. The purpose of this approach is to evaluate different rain levels and propose thresholds from the found results. PR_g is calculated using the following ratio:

$$PR_g=\frac{PR_a-PR_b}{PR_b}\times 100 \quad \text{(Equ.5)}$$

Where, PR_a and PR_b is the PR after and before rain event, respectively. Other expressions were proposed and presented in [10].

The proposed model is trained based on the following filters:

GTI filter: In this step, $B_{GTI}$is normalized to 0 and 1 values in order to maintain and determine the sunny days. The equation 6 presents the filter used in this case:

$$B_{GTI} = \begin{cases} 1, & GTI\geq 600\ W/m^2 \\ 0, & \text{otherwise} \end{cases} \quad \text{(Equ.6)}$$

Figure 1 shows an example of $B_{GTI}$for one year including a zoomed-out graph.

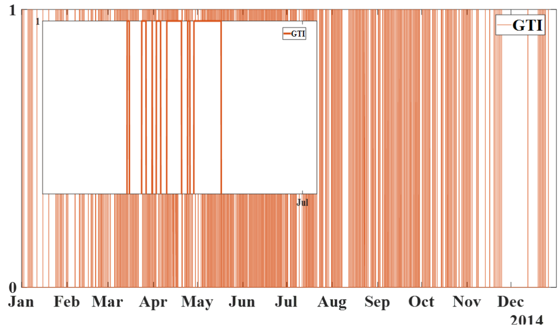


Figure 1. Sample B_{GTI} for one year

R_f filter: After importing rainfall data, normalization is also applied for these data as it is described in the following expression:

$$R_f = \begin{cases} 1, & R_f\geq 0.1\ mm \\ 0, & \text{otherwise} \end{cases} \quad \text{(Equ.7)}$$

The studied regions are characterized by long rainy periods. Hence, successive rainy days are merged into one R_f value if there are no sunny days in between.

Merging $B_{GTI}$and R_f: In this step, $B_{GTI}$and R_f are merged into one spreadsheet to facilitate the search for levels of rainfall events and the calculation the PR_g which corresponds to the sunny days before and after the rainfall events. Figure 2 presents an example of merged $B_{GTI}$and R_f over one year.

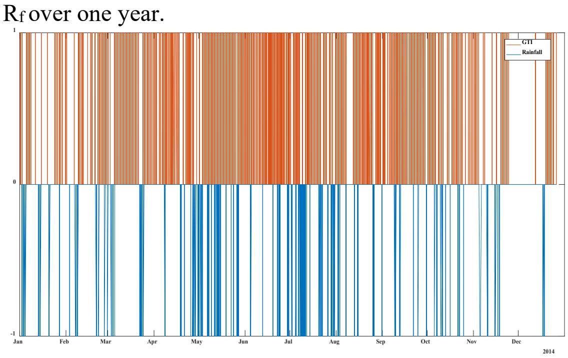


Figure 2. Merged B_{GTI} and Rf for one year

In this study, calculated PR is based on the application of some filters, indeed, filtering GTI between 700 W/m^2 and 900 W/m^2, and daily PR between 0.65 and 1.

PR_g indicates the impact of R_f on the PR and as described above, it is calculated using PR_a and PR_bwhich corresponds to the sunny day before and after a rainfall event. The proposed methodology contains three key elements:

1. Performance ratio (PR). This calculated factor describes the performance of the PV system. PR is specific to the site's location.
2. Performance ratio gained (PR_g). This parameter is calculated to determine the impact of rainfall on the PR of the PV systems.
3. Cleaning threshold. This presents the daily amount of rain required to clean the PV system. Figure 3 presents a flowchart which resumes the proposed MATLAB algorithm and the applied filters.

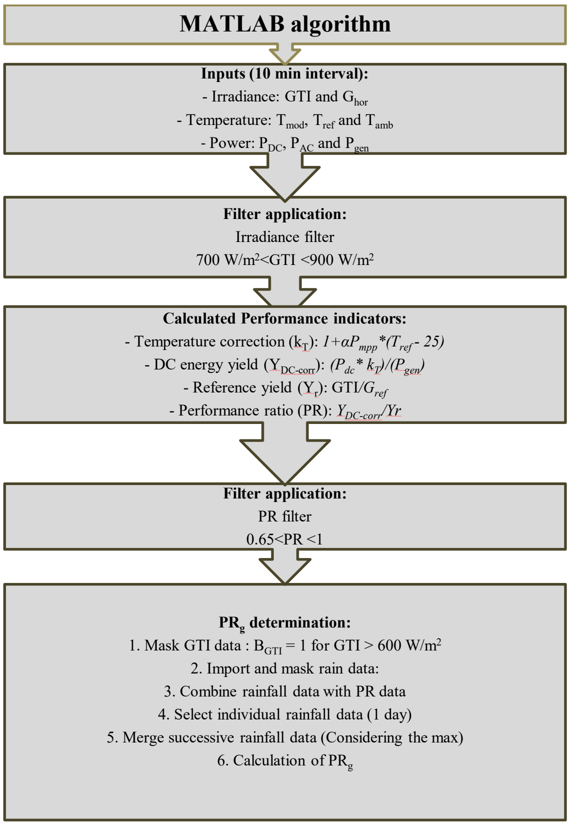


Figure 3. MATLAB Algorithm

4 RESULTS

4.1 Long-term PR

Figure 2 presents the PR of the three studied PV systems, as well the linear degradation per year is shown using the linear regression fit. For Tiergarten systems, the discontinuities showed in its graphs are belong to cleaning events (every 4 years).

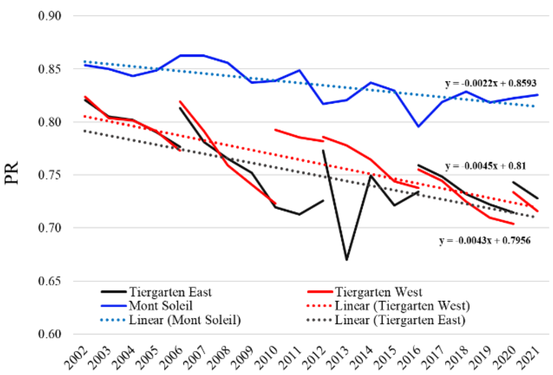


Figure 4. Long-term PR of studied PV systems

Total daily precipitation for 20 years under the studied regions is presented in Figure 3. In some cases, high amount of rain was recorded per day, which surpasses 80 mm.

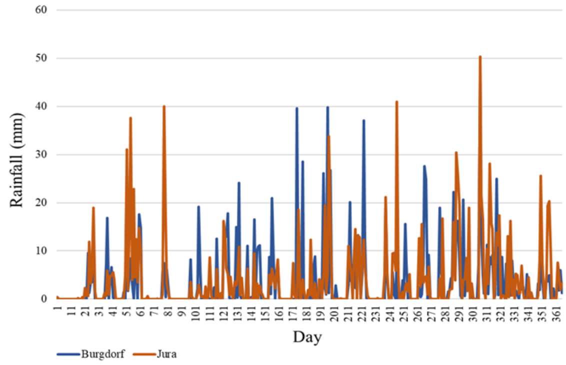


Figure 5. Example of one year of daily precipitation in the studied regions

Rainfall patterns are presented in Figure 4 for the studied regions. It is shown that for both areas, rainfall level of (0.1-1.1) mm presents the largest number of rainy days.

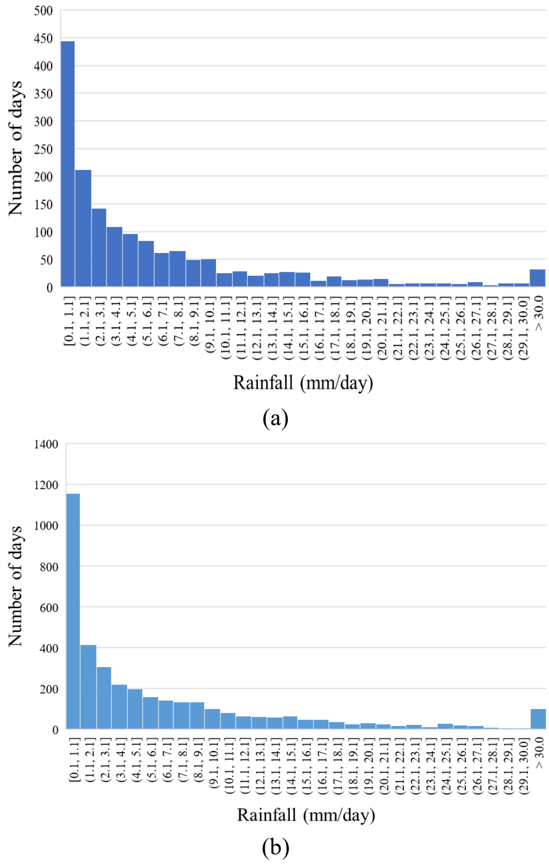


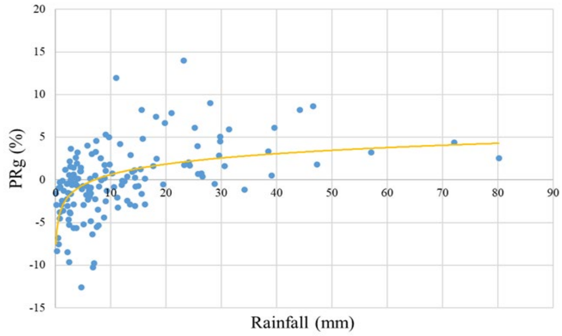
Figure 6. Rainfall data for the 2002 to 2020 period for Burgdorf (a) and Mont-Soleil (b) sites

4.2 Impact of rainfall on PR

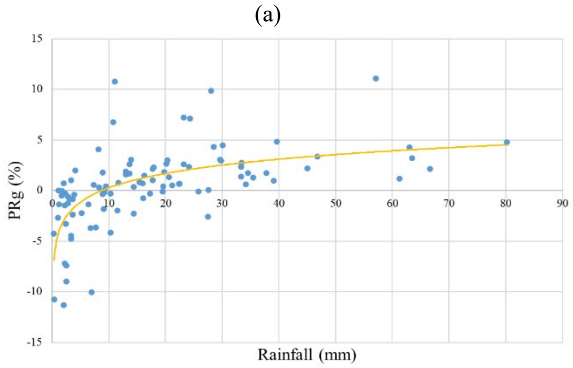
This study shows the correlation between the intensity of precipitation events and the self-cleaning effect of the long-term performance of PV systems by means of a scatter plot showing rain intensity versus performance ratio gain PR_g (Figure 7). Negative values indicate that corresponding rainy events could not clean the PV system, either the amount was not enough or the presence of successive rainy days.

The scatter plot data presented in Figure 7 is approximated using the logarithmic fit function because it shows the best fitting to the trend of the results. It is expressed as follows:

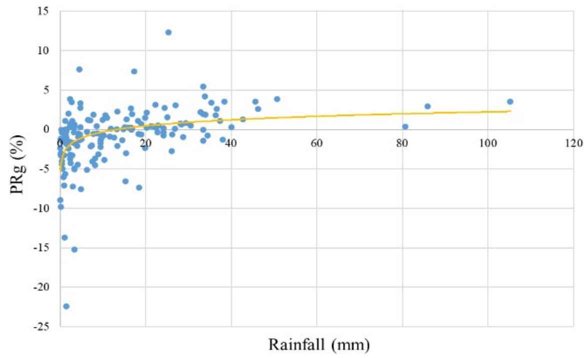
$$y = a\ln(x) + b \qquad \text{(Equ.8)}$$



(a)



(b)



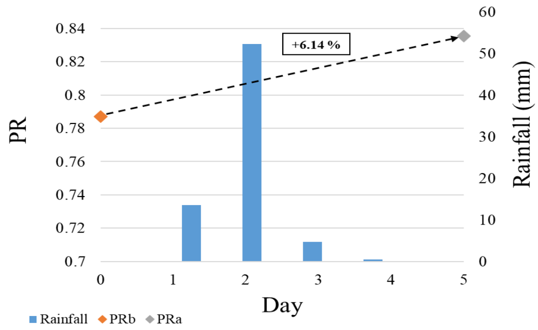
(c)

Figure 7. Gained PR (PR_g) and rainfall for Tiergarten West (a), Tiergarten East (b) and Mont-Soleil (c)

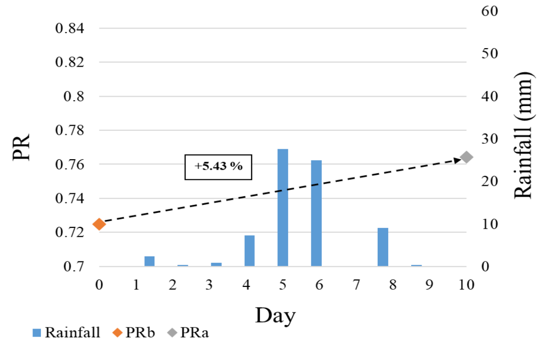
4.3 The performance of PV system after rainy days

In the studied regions, most of rain events occur for many successive days (more than 3 days). It is found that these rainy periods have positive as well as negative effects on the performance of the investigated PV systems. To illustrate the effect, some rainy periods were selected to show examples of both effects by presenting the variation of PR before, during and after the rainy period.

4.3.1 Positive effect



(a)



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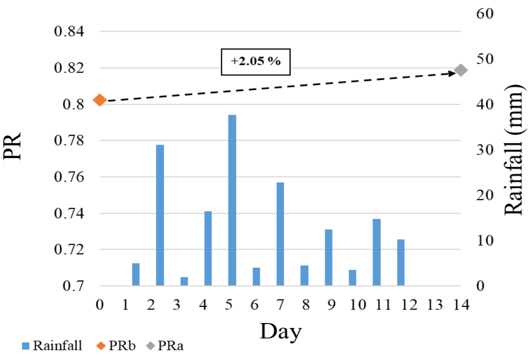
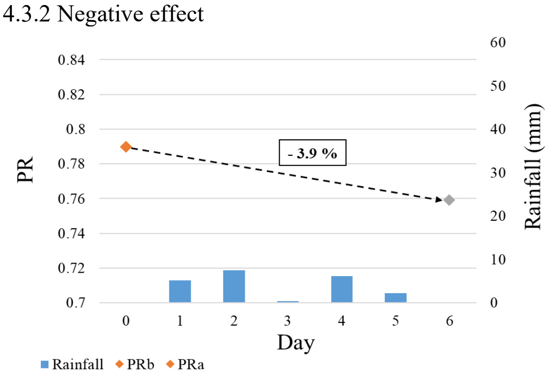


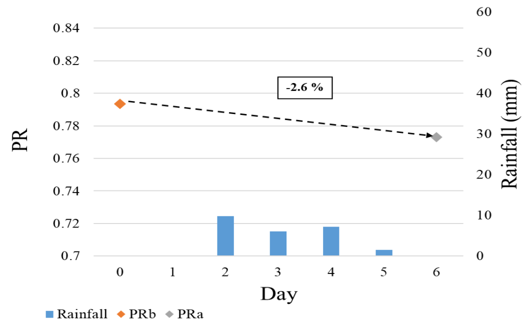
(c)

Figure 8. Positive impact of successive rainy days

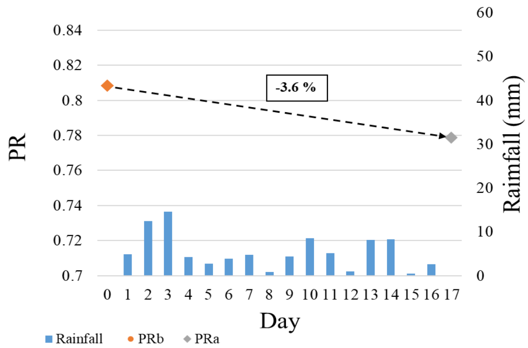
4.3.2 Negative effect



(a)



(b)



(c)

Figure 9. Negative impact of successive rainy days

4.4 Amount of Rainfall to Clean Modules

In order to quantify the effect of self-cleaning on the PR of all studied PV systems, thresholds were calculated as function of rainfall. As presented in Table 1, rainfall events were provided as ranges or levels and the results were presented in the minimum, maximum and average formats. The cleaning success of the rainfall increases with its intensity depending on the PV system. In the average term, 15 mm per day could be a significant amount to clean the PV systems. For Tiergarten system, the gain of PR increased from 1 % to 5 % for rainfall levels of 15 mm to +25 mm per day, respectively. While for Mont-Soleil system, the PR_g reached 4 % for rainfall amount greater than 25 mm.

Table 1. Thresholds of studied PV systems based on different rainfall ranges

	Rainfall (mm/day)	0.1-5	5-15	15-25	+25
Min. PR_g(%)	*Tiergarten West*	-12.6	-10.3	-2.9	1.8
	Tiergarten East	-11.3	-10	-0.8	1.2
	Mont-Soleil	-22.4	-7.1	-5.4	0.4
Max. PR_g(%)	*Tiergarten West*	3.7	5.3	8.2	11.3
	Tiergarten East	2	6.7	7.2	10.5
	Mont-Soleil	2.7	2.3	7.4	8
Av. PR_g (%)	*Tiergarten West*	-1.9	-0.9	2.7	4.8
	Tiergarten East	-2.9	0.2	1.8	4
	Mont-Soleil	-2.9	-1	0.2	3.7

5 CONCLUSION

In the current work, self-cleaning of different PV systems were analyzed using 25-30 years of data in Switzerland. MATLAB software was used to prepare and analyze the energy yield data, the performance ratio (PR) is calculated. To understand the self-cleaning mechanism, PR before and after precipitation events is calculated to determine a performance gain index (PR_g). The latter is correlated to the intensity of various precipitation events. Moreover, frequency and threshold of rain events are presented for each investigated location. Overall, it could be considered that 15 mm of rainfall is a threshold for the PV modules to get cleaned, and below this value, the precipitation events rather cause soiling of the modules.

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