Evaluation of Performance Improvement by Cleaning on Photovoltaic Systems

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Abstract. To keep high-performance operations in photovoltaic system is an important task. However, solar panels are subject to pollution in the natural environment. Possible pollutions include dust in the air, feces in birds and dust from burning materials, etc., which can cause solar energy performance reduced. In this paper, the effects by manual cleaning and natural cleaning are investigated and the result is aimed to help manager to determine the timing of cleaning. The Array Ratio (RA) was used to evaluate the daily power generation performance and various conditions which can prevent from obtaining reliable RA values were addressed. Experiments were conducted to verify the proposed approach. The results showed that the first manual cleaning has a significant cleaning effect of 10.11% and the second manual cleaning effect only 2.03% since before the cleaning there were several heavy rains, resulting in natural cleaning of the plant.

Keywords: Data analysis · Photovoltaic system · PV module cleaning · Performance evaluation · Array Ratio

1 Introduction

Maintenance of solar panels is important which influences power production. One of the maintenance problems is to determine when to clean dirty solar panels caused by dust or other pollutions. Over cleaning can lead to wasted cost and not enough cleaning leads to reduced production. Especially in a tropical island-type climate in Taiwan, it rains frequently in some seasons, which results in cleaning effect of the dirty solar panels, referred to as natural cleaning in contrast to manual cleaning by maintenance personnel. It is necessary to investigate the cleaning issue of solar plants in Taiwan.

Pollution loss varies in different areas. In the cleanest United Kingdom, if there is no cleaning in a month, the sunshine intensity will decrease by 5% ~ 6% and In Sudan, the reduced intensity of sunshine will be 9 times that of the UK. In cooler and wet environments, the accumulated pollutants may include dust in the air, feces from birds and other animals, dust from burning materials, leaves or pollen [1].

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The solar panels with loss of output caused by the natural environment pollution needs to be maintained by cleaning. Relevant research suggests using system parameters with comparison between cleaned solar panels and contaminated solar panels to build cleaning models. To determine the frequency of solar panel cleaning, a related data model is used to dynamically updating the recommended cleaning frequency through clean and contaminated solar panels [2]. To determine the economic cost of cleaning, power production efficiencies in Perth, Australia and Nusa Tenggara Timur (NTT), Indonesia were evaluated [3]. The energy output of the module was normalized by the maximum energy output under standard test conditions (STC) and compared. The results showed that the average decline rate of maximum output per month was 4.5% and 8%, respectively. The study found that the NTT solar plant needs manual cleaning in October, and the Perth solar plant requires manual cleaning in August and October. To determine the recommended cleaning frequency for a year, researchers used Helioscope with simulation of solar plant and determined 10% and 15% soiling levels by the dust transparent instrument, which is closest to those of the local Algerian Sahara sites desert, and then does not clean the solar case for one year [4]. It is found in the study that cleaning twice a year is profitable.

Most of the research on the cleaning frequency like those mentioned above was conducted under controlled environment with carefully maintained solar panels. To the best of our knowledge, there is no investigation on operational solar-power plants which connected grid network. In an uncontrolled environment, additional issues need to be taken into consideration, including module failure, the angle of the sun photometer, the direction of the solar panels, etc.

In this paper, we propose an approach to measure power production improvement resulted from cleaning on operational solar-power plants. The result is valuable and can help to determine the proper time for panel cleaning. We considered the additional issues mentioned above and avoided the need for parameters which are expensive to obtain. In essence, we monitor power production of the plants under good weather. Low power production indicates cleaning shall be scheduled. The approach requires only power output, irradiance, and string capacity.

2 Method

The solar plant used in this study located in central Taiwan is operational and connected to the grid network. The total capacity of the plant is 484.12 kw.

Array Ratio (RA) [5] of photovoltaic system was used to observe power production changes caused by natural environment pollution, natural cleaning by rainfall and manual cleaning. The approach we propose is to monitor the change of RA along time, especially, the RA before and after manual cleaning as well as natural cleaning. However, the calculation of RA is not a trivial task. An inappropriate conduct could lead to results which are not interpretable. In the section, we propose the method which can help to acquire reliable RA values and thus the change of RA values along the time.

2.1 Array Ratio

RA was used to evaluate production performance of individual panel strings every five minutes. To calculate RA, the ratio between production efficiency PE and normalized irradiance IRR, as expressed in Eq. (1). PE is measured with the ratio between string output referred to as DCKW and module capacity. IRR is the ratio between the actual amount of irradiance, irradiance, and under the standard test condition (STC), namely, 1000 w.

$$RA = \frac{PE}{IRR} = \frac{DCKW/capacity}{irradiance/1000} \tag{1}$$

RA in Eq. (1) for each string is calculated every five minutes. The daily value $\mathrm{RA_{day}}$ is computed by aggregating all the calculated RA values obtained in a day and from all the strings, as shown in Eq. (2) where N is the set of modules in the plant, n indicates a single module, T is the set of total time points involved in the calculation, and t indicates a single time point. In this study, T includes the time points in the afternoon from 12:00 to 15:00.

$$RA_{day} = \frac{1}{|T|}\sum\nolimits_{t\in T}\frac{1}{|N|}\sum\nolimits_{n\in N} RA_{t,n} \tag{2}$$

2.2 Factors Affect RA Values

The idea behind our approach is that RA shall keep roughly stable under normal operation conditions. However, unexpected situations such as bad weather, cloud, failed devices, panel direction, etc. can result in abnormal values. We thus compute RA under certain conditions only to avoid anomaly. The conditions keeping valid RA include irradiance threshold, effective PE range and RA difference threshold. There are no theoretical rules for setting those parameters. Therefore, we resort to extensive experiments looking for appropriate thresholds.

First, a data point is taken into account only which irradiance is higher than the irradiance threshold. For the points passed the first condition, their PE is calculated. Second, the effective PE range is set to eliminate faulty devices, which yield low power. Third, since RA shall be stable under good weather, abrupt change of RA shall be excluded. $\mathrm{RA_{slope}}$ in Eq. (3) measures the RA change between two time points.

$$RA_{slope} = |RA_{t+1} - RA_t| \tag{3}$$

2.3 Effect of Panel Cleaning

After cleaning, RA shall improve. The percentage of improvement is used to quantize the effect of solar panel cleaning, as expressed in Eq. (4) where the parameter $\mathrm{RA_{clean}}$ indicates the daily average RA after cleaning and the parameter $\mathrm{RA_{dirty}}$ represents the daily average RA before cleaning.

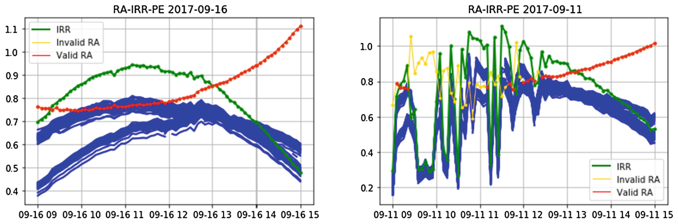
$$RA_{imp} = \frac{RA_{clean} - RA_{dirty}}{RA_{dirty}} \times 100\% \tag{4}$$

3 Conditions for Valid RA Values

3.1 Different Angles of Modules and Pyrheliometer

In a solar plant, there may be panel strings that are either eastward or westward. Since the sun rises eastward and falls westward, the eastbound solar panels will produce more power in the morning then the westbound panels while the westbound panels will produce more power in the afternoon. Similarly, pyrheliometer can be installed horizontally or along with the angle of the panels.

Figure 1(a) shows RA value will be between 0.7 and 0.8 in the morning while between 0.8 and 1.1 in the afternoon. In addition, the pyrheliometer was installed along with the panels eastward. The RA value higher than 1.0 will not be a problem since the comparison of the RA values is made in the same power plant rather than different ones which may have a different angle of the pyrheliometer



(a) (b)

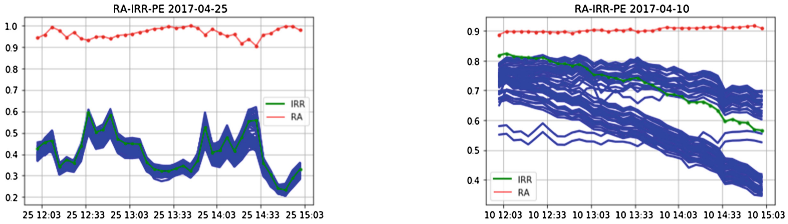
Fig. 1. IRR, PE and RA under (a) clean sky in all day and (b) shading in the morning. (Color figure online)

Figure 1(b) shows that the weather in the morning is unstable indicated by the unstable irradiance (depicted in the green line), and consequently yield the unstable, abnormal RA values (the yellow line) in the morning which are considered invalid RAs and excluded. Only the high, stable RAs in the afternoon are counted, which leads to a high average RA for the day. In this study, the daily average RA is calculated with valid RAs in between 12:00 $\sim$ 15:00.

3.2 Threshold of Irradiance

Irradiance can be unstable due to unstable weather such as cloud. Consequently, RA values can be unstable as well. We need to exclude those data points which are collected under unstable irradiance.

Figure 2(a) shows that RA is unstable, usually becomes higher, in low irradiance. Figure 2(b) shows RA appears stable and will not be elevated under stable irradiance in good weather.



(a) (b)

Fig. 2. RA with different irradiance levels: (a) low irradiance, (b) normal irradiance.

To acquire a proper threshold for the irradiance, we conducted experiments with various settings. Figure 3 shows at the irradiance threshold of 400 W/m2, there are days which have extreme high daily RAs. After inspection, those values are abnormal. The results with 500 W/m2 and 600 W/m2 are quite close. We use 500 W/m2 as the threshold for the subsequent experiments to avoid excluding too many points.

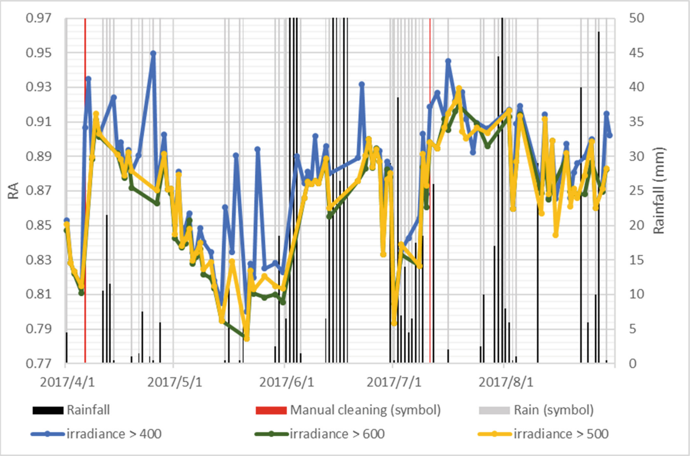
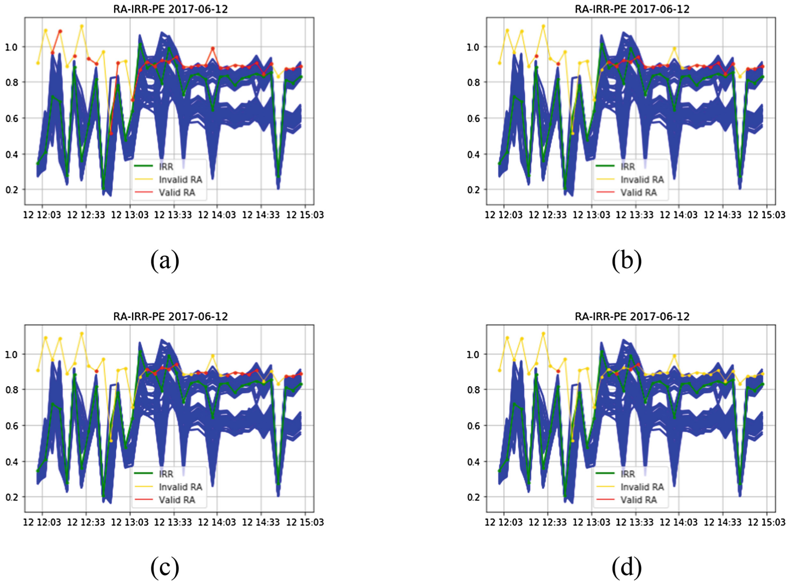


Fig. 3. Distribution of daily RAs with different irradiance thresholds.

Difference threshold of RA

Up to this point, the valid data points satisfy the following conditions: the time period for data points is 12:00 ~ 15:00, and the irradiance threshold is > 500 W/m2. In addition, the number of valid RAs shall be at least 20 and otherwise we ignore that day, i.e., do not calculate its daily average RA.

Still, some abnormal RAs can be observed as shown in Fig. 4(a). To tackle this problem, we further set a slope threshold referred to as $\mathrm{RA}_{\mathrm{slope}}$. As can be seen in Fig. 4(b) $\sim$ (d), with smaller $\mathrm{RA}_{\mathrm{slope}}$, the number of valid RAs (indicated by the red dots) decreases. The results with $\mathrm{RA}_{\mathrm{slope}} \leqq 0.07$ and $\mathrm{RA}_{\mathrm{slope}} \leqq 0.05$ are about the same. In Fig. 4(d), it is clear that the threshold $\mathrm{RA}_{\mathrm{slope}} \leqq 0.03$ is to rigid, leading to the exclusion of too many data points.



(a)

(b)

(c)

(d)

Fig. 4. The difference threshold of $\mathrm{RA}_{\mathrm{slope}}$: (a) not setup threshold of $\mathrm{RA}_{\mathrm{slope}}$, (b) $\mathrm{RA}_{\mathrm{slope}} \leqq 0.07$, (c) $\mathrm{RA}_{\mathrm{slope}} \leqq 0.05$, (d) $\mathrm{RA}_{\mathrm{slope}} \leqq 0.03$. (Color figure online)

Figure 5 shows the RA results calculated with different $\mathrm{RA}_{\mathrm{slope}}$ thresholds over a long period of time. As demonstrated, with $\mathrm{RA}_{\mathrm{slope}}$ threshold 0.07 it seems there are still many abnormal points. With $\mathrm{RA}_{\mathrm{slope}}$ threshold 0.05, it seems most of the daily RA values are reasonable. Nevertheless, more observations with additional experiments are needed. With $\mathrm{RA}_{\mathrm{slope}}$ threshold 0.03, the line becomes smoother. However, only a few days are left and many valid days are excluded.

3.3 Effective Range of PE

It has been observed that the module fault occurred in a string will produce reduced power. In order to avoid including the fault module to the average calculation, production efficiency (PE) is aggregated for only a certain range of the individual PE values. Through the determination of the previous experiment, the condition increased the $\mathrm{RA}_{\mathrm{slope}} \leqq 0.05$ in this experiment. This experiment conditions includes:

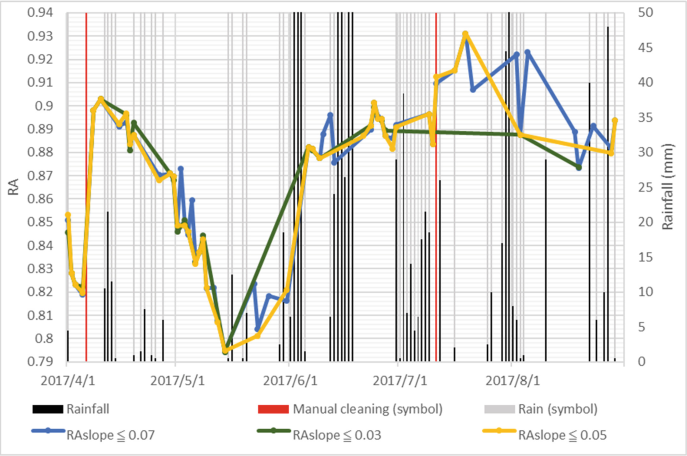
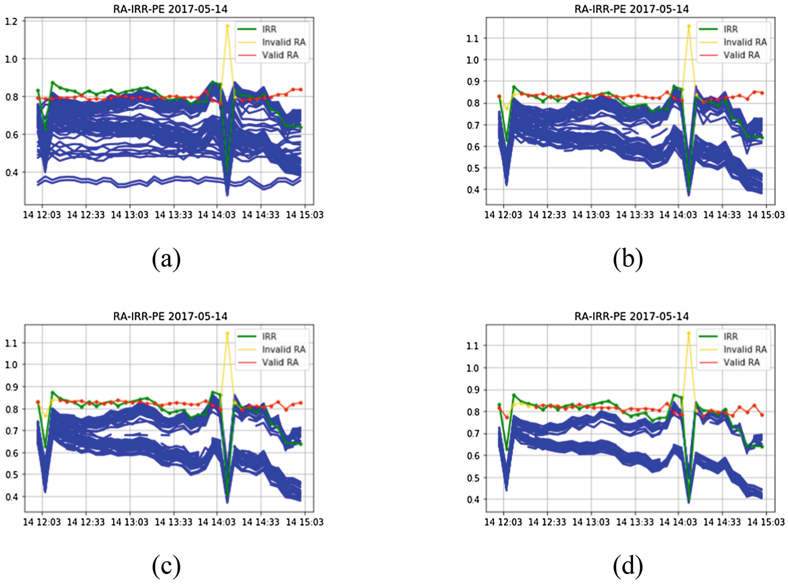


Fig. 5. The difference threshold of RA_{slope}.

experimental time 12:00 ~ 15:00, RA effective points ≧ 20, threshold irradiance > 500 W/m2, threshold RA_{slope} ≦ 0.05.

Figure 6(a) presents the result without setting the threshold. It can be seen that there are several strings which have low PE values (indicated by the blue lines). Among those, two are quite evident, with the values less than 0.4. In Fig. 6(b) the effective range of the PE is set to the median ± 0.07. We can still observe low PEs. In contrast,



(a)

(b)

(c)

(d)

Fig. 6. The difference for effective range of PE: (a) not setup effective range, (b) PE median ± 0.07, (c) PE median ± 0.05, (d) PE median ± 0.03. (Color figure online)

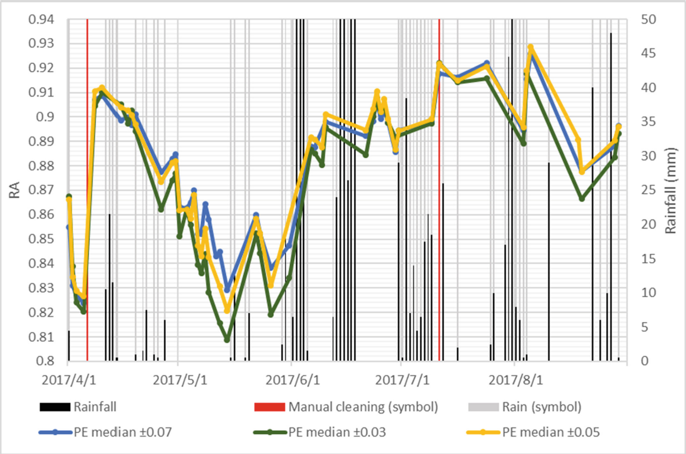


Fig. 7. The difference for effective range of PE. (Color figure online)

in Fig. 6(d) too many PEs are excluded and only a few strings remain. Therefore, it seems better to set the retention range of the PE by the median ± 0.5.

Figure 7 shows the RA results over a long time. No significant difference in the trend of the lines can be observed. However, we can see that a small range of PE values can result in low RA values. In particular, the green line representing the medium ± 0.03 is clearly low than the other two lines in several portions.

4 Experimental Results

The experiment is to observe the long-term change of RA from 2017/4/1 to 2017/8/31. The daily RA values were calculated for days under stable weather or at least having certain number of valid data points. The conditions for valid RA values are specified as the following: the time period is taken in between 12:00 and 15:00, the number of valid RA values shall be ≧ 20, the irradiance threshold > 500 W/m2, the threshold $\mathrm{RA}_{\mathrm{slope}}$ ≦ 0.05, threshold PE range by PE median ±0.05.

Figure 8 shows the long-term RA change from 2017/4/1 to 2017/8/31 with manual cleaning on 2017/4/6 and 2017/7/11. We can see clearly that RA improves after manual cleaning. In early May, there was nearly no rains such that the RA decreased gradually. In early and mid-June, there were many heavy rains, which led to significant increases in RA. In late July, raining for several days also led to a slight increase in RA.

Table 1 shows the improvement after the two manual cleanings. The improvement after the first cleaning on 4/6 is significant, i.e., 10.11%. The improvement made by the second cleaning on 7/11 is marginal, i.e., 2.03%. The reason is because there were several heavy rains in June and July which have cleaned the panels and improved the RAs to near 0.9, leaving little room for improvement by manual cleaning. Having the analysis tool like shown in Table 1, the manager can decide when is the proper time to conduct manual cleaning of the solar-power plant.

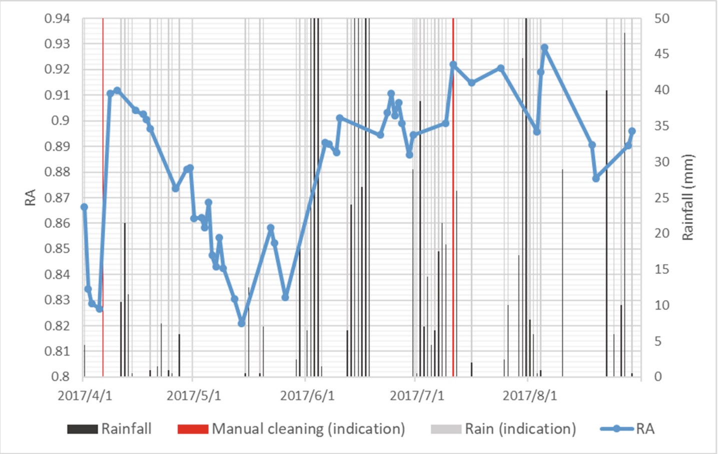


Fig. 8. Long-term observation of RA change, rainfall and manual cleaning.

Table 1. Efficiency improvement after cleaning on 4/6 and 7/11

Date	RA_{day}	RA_{imp}
2017/4/5 (dirty day)	0.824	
2017/4/8 (clean day)	0.907	
2017/4/6 (cleaning day)		10.11%
2017/7/9 (dirty day)	0.898	
2017/7/16 (clean day)	0.916	
2017/7/11 (cleaning day)		2.03%

5 Conclusion

In this study, we employed data analysis techniques to investigate the effect of solar-panel cleaning by analyzing collected data from a solar-power plant in central Taiwan. The cleaning effect is measured by the improvement on the daily RA value after the cleaning. Calculating the RA value is not a trivial task and needs to consider factors which prevent from obtaining reliable RAs. We discussed the factors and proposed methods to tackle the problems. Extensive experiments were conducted to verify the proposed methods. The results look promising. Consequently, the proposed approach can be used to help managers to determine when to clean solar-power plants such that a large improvement of power production after cleaning can be obtained.

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