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Thermal Impact on the Performance Ratio of Photovoltaic Systems: a case study of 8000 photovoltaic installations

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Abstract:

Investigating the thermal impact including the fluctuations of the solar irradiance and ambient temperature of photovoltaic (PV) systems is a topic of great interest by industry and policymakers, due to the limited case studies reported so far by the PV research community. Therefore, this article presents the analysis of 8000 PV systems distributed across England using the well-known metric, monthly performance ratio (PR). The PV systems were operated over five years, while the PR is calculated using the newly developed model by the US national renewable energy laboratory (NREL). Remarkably, it was found that the average monthly PR for all examined PV systems is equal to 85.74%, where the Midlands region in the UK has the highest monthly PR of 88.12 %. We have also investigated the seasonal thermal impact on the performance of PV systems, where it was concluded that Spring and Summer seasons intend to have higher monthly PR compared to Autumn and Winter. Finally, a detailed experiment of three different PV modules affected by various hotspots, including cell-based and string-based, will be comprehensively discussed.

Keywords: Photovoltaic systems; Performance Ratio; Thermal Imaging; Hotspots.

1. Introduction

By the end of 2019, the UK solar photovoltaic (PV) installations capacity reached 15 GW. Several studies have deliberated the performance of PV systems [1]. However, there are few publications which study the performance of PV installations across the UK, particularly relating to the thermal impact including the variations of the solar irradiance and ambient temperature among multiple regions across the country.

Studying the performance of PV installations are predominantly calculated and exhibited using the analysis of the monthly or even daily performance ratio (PR). The PR is a popular metric used to indicate the total generation of the output power of PV installations [2]; wherein theory, 100% shows no losses associated with the PV installation. In existing PV installations, as a worldwide point of view, the PR is usually ranging from as low as 10-20% up to 95%.

Several environmental conditions influence the PR ratio, including, but not limited to, the thermal variations including the amount of solar irradiance received by the PV modules and the fluctuations in the ambient temperature [3]. Another good example of the environmental conditions is the wind speed and the humidity, as PV systems perform better when the wind speed is at greater levels or less humidity in the PV location [4].

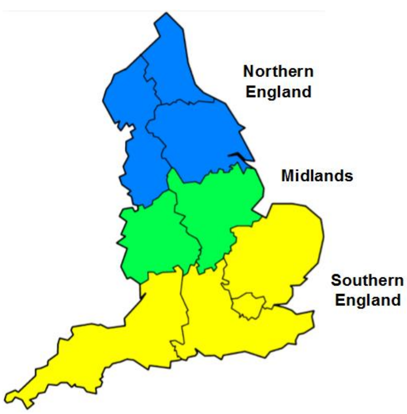
Besides, some research correlates the performance of PV installations with the season of the year [5]. This is a fair comparison, as in the winter seasons, shading is likely to occur due to the moving clouds, resulting in a significant drop in the PR ratio. In contrast, summer seasons show higher PR ratios as the clear sky, and overcasting conditions are likely to happen.

According to other research findings [6], the PR ratios of PV systems are likely to drop in winter seasons because of the presence of hotspotting phenomenon. Hotspotting occurs when one or multiple solar cells operates in the breakdown, hence, resulting in a significant drop in the output current while also maintaining a substantial increase in the temperature of the affected cells. The main reason of the presence of hotspots in PV modules is due to the thermal fluctuations of the solar and ambient temperature affecting the PV modules [7], in addition, hotspots are likely to occur to the increasing amount of shading on solar cells. Nowadays, thermal imaging cameras are habitually used to detect hotspots in PV modules, where it can be easily identified [8, 9].

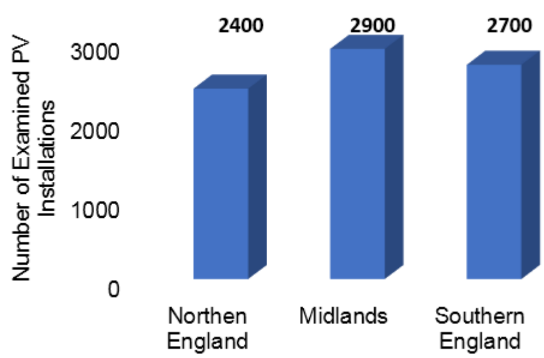
The main contributions of this article are, (i) examining the monthly PR of 8000 PV installations distributed across England, (ii) analysing the seasonal impact on the PR for the PV installations located in the Midlands, and finally, (iii) investigating the effect of hotspotting phenomenon on the PR of different PV modules.

2. Examined PV installations

In this study, we have examined 8000 crystalline silicon (c-Si) made PV installations distributed across England, operating for five years; 2015 to 2019. Fig. 1(a) shows the three regions of England, including northern England, the Midlands, and southern England. In Fig. 1(b) we show the number of inspected PV installations in each region. All PV installations are for residential use with a capacity ranging from 1.2 to 3.8 kWh. The PV generation data is collected via the MgDB database [10], where only the monthly dataset is considered in our investigation of the PV performance analysis.



(a)



(b)

Fig. 1. (a) Northern England is shown in blue, the Midlands as green, and southern England as yellow, **(b)** Number of examined PV installations distributed across each location.

3. Monthly PR analysis

The calculation of the monthly performance for all examined PV systems has been done using the well-established PR calculation model of the US national renewable energy laboratory (NREL) [11]. The PR at standard test conditions (STC) is calculated, where the solar irradiance is equal to 1000 W/m^2. The ambient temperature of 25 °C, PR is the uncorrected performance ratio, f_T is the corrected temperature of a given PV system, f_G is the corrected solar irradiance; the following equation gives the monthly PR at STC:

$$Monthly\ PR\ at\ STC = \frac{PR}{f_T \times f_G} \quad (1)$$

The f_T and f_G are given the following equations, where S is equivalent to the temperature coeffect of the PV installation (taken from the datasheet of the PV modules and has a negative value), T_{STC} is equal to 25 C, while the irradiance-weighted mean cell temperature is given by $T_{weighted}$. According to the f_G calculation, c is the reducing in the PV system efficiency due to the decrease of the solar irradiance, the typical value of c is 0.031 for c-Si PV modules, $G_{weighted}$ is the weighted irradiance in the plane of the PV array for the commencing month, and last, G_{STC} is equal to 1000 W/m^2.

$$f_T = \left[1 - \frac{S}{100}\left(T_{STC} - T_{weighted}\right)\right] \quad (2)$$

$$f_G = \left[1 + c\ln\left(\frac{G_{weighted}}{G_{STC}}\right)\right] \quad (3)$$

The average monthly estimated $T_{weighted}$ and $G_{weighted}$ for all 8000 examined PV installations are shown in Fig. 2; five years has been taken into account as these PV installations are operating over the last five years. Correspondingly, these parameters of the weighted temperature and irradiance are highly affected by the season of the year. As a result, there is a substantial seasonal and inter-annual disparities in the analysis of the PR which will be discussed in the following sections.

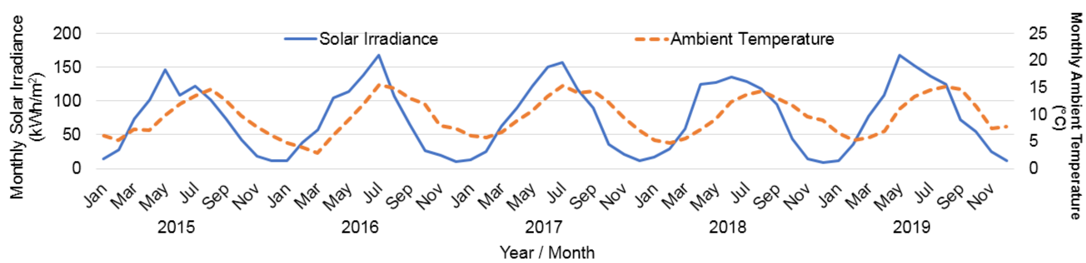


Fig. 2. Monthly solar irradiance and ambient temperature in England from 2015 to 2019.

4. Results and discussions

The distribution of the monthly-integrated PR is presented in Fig. 3. The shape of the distribution is characterised using the Weibull function [12], the rationale of using this type of distribution since it is well-suited with datasets that have an insignificant skew in the lower range. And as presented in Fig. 3, the data shape is concentrated in the ranges of 60-95%. According to the monthly PR calculated throughout 5-years, it was found that the Midlands has the largest "scale" monthly PR of 88.12%. Southern and northern England have a monthly PR of 85.12% and 83.98%, respectively.

According to the historical thermal environmental events "variations of the solar irradiance and ambient temperature", the Midlands has the lowest fluctuations during the seasons of the year [13], hence, thermally

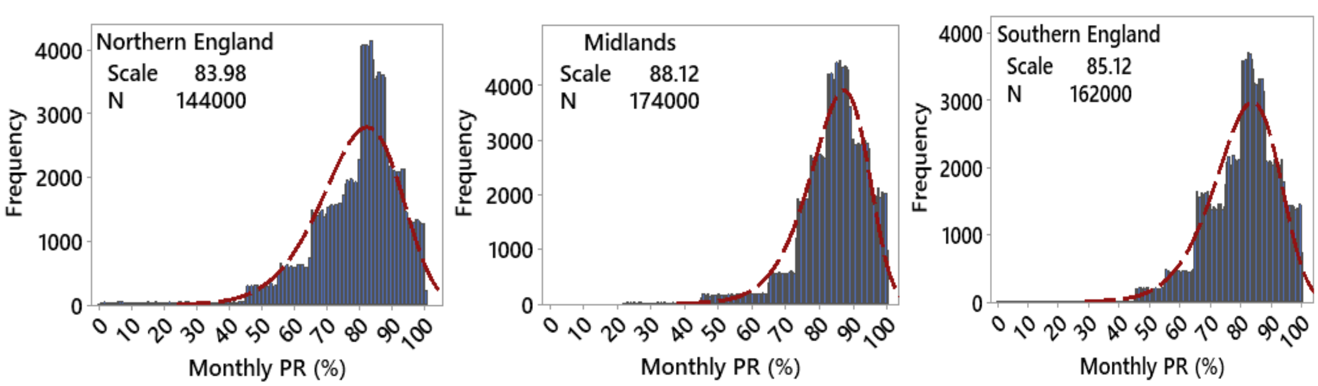


Fig. 3. Monthly calculated PR for northern England, the Midlands, and Southern England.

speaking, there is less thermal impact on the performance of the PV installations; therefore, the Midlands as excepted have the highest possible monthly PR ratio. In contrast, Northern England have the highest rates of thermal instabilities. Therefore, PV installations located in Northern England have the lowest monthly PR of 83.98%.

As the Midlands have the highest monthly PR, we have calculated the seasonal impact on the performance of the PV installations located in this region; results are presented in **Fig. 4**. It is noticeable that during the spring seasons (March-May) the PV installation intends to have the highest possible monthly PR of 91.62%, however, as expected, the lowest monthly PR of 84.04% is found during the Winter season (December-February) as during these months the PV installations are predominantly affected by shading conditions [**14**], and as a result, the existence of hotspots become the main reason of the decay in the performance ratio.

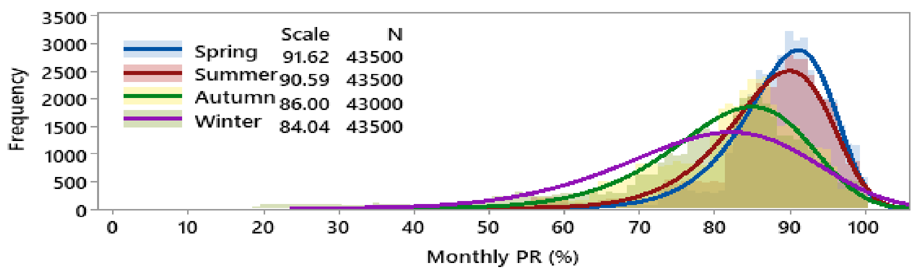


Fig. 4. Seasonal calculated PR for the Midlands.

To examine the impact of hotspots on the performance ratio of PV modules, we have experimented for a period of 12-months, three adjacent PV modules affected by different types of hotspots. The thermography images of the examined PV modules and their daily PR analysis is presented in **Fig. 5**. The first PV module (no. 1) is affected by two hotspotted solar cells, second PV module (no. 2) is affected by multiple hotspots, while the last PV module (no. 3) is affected by hotspotted PV string.

During the 12-months experiment, the daily PR ratio is equal to 90.64% for the first PV module. Increasing the number of hotspots in the PV module, as in PV module no.2 would result in a decrease in the total power generation; as a result, the daily PR drops at a low level of 79.20%. The lowest daily PR of 65.35% is determined for the last PV module because this module is suffering from a high rate of power loss due to the presence of the hotspotted PV string.

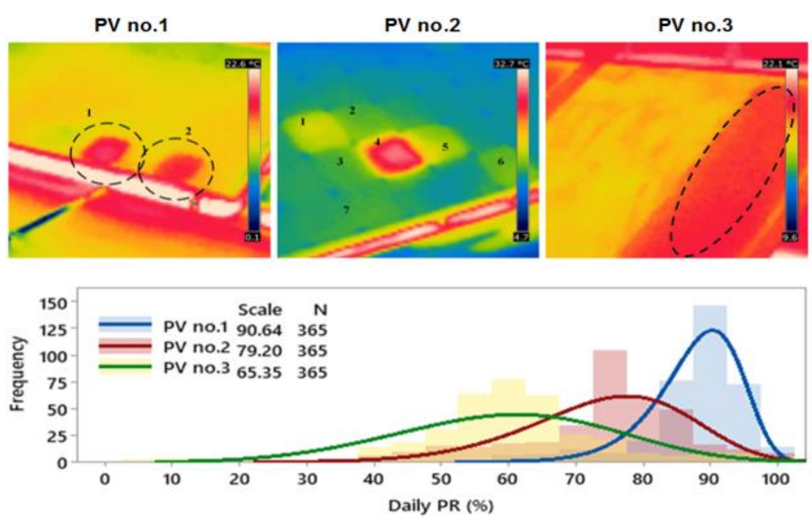


Fig. 5. Calculated PR for three different PV modules affected by different hotspotting conditions.

5. Conclusions

To conclude, in this case study, we have analysed the PR of 8000 PV modules distributed across three regions in England using the well-known PR method of NREL. It was observed that the Midlands have the highest monthly PR, while the lowest is found for Northern England. In addition, the seasonal impact on the PR analysis was determined using the same method for all PV installations located in the Midlands, where it was observed that Spring and Summer seasons intend to have higher monthly PR compared to Autumn and Winter. Furthermore, a case study on three different PV modules affected by various hotspotting conditions have been reported. Increasing hotspots in PV modules would result in a greater drop in the daily PR. There is a significant drop in the daily PR for PV modules affected by hotspotted PV strings.

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