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PV generator nominal power estimation using a ground sensor and the PVLIB online irradiance database

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Abstract. The nominal power of a photovoltaic generator is a crucial parameter. For instance, it is a required input parameter for modelling the energy produced by a PV system. Determining the nominal power in-situ requires measuring the irradiance and module temperature. Usually, the irradiance is measured with a sensor placed on the ground and at the plane of the array. The present work first compares the irradiance measurements of a calibrated PV module with the openly available irradiance database PVLIB. Second, it contrasts the daily estimated nominal power values considering both irradiance sources. The results indicate that the irradiance database is suitable to calculate the nominal power.

1. Introduction

In 2020, more than 127 GW of photovoltaic (PV) capacity or nominal power had been installed, and global solar installations could hit a record of 180 GW by the end of 2021 [1]. Grid-connected, utility-scale systems are the primary type of installed configuration. The nominal power (P_M^*) represents the maximum power point of a PV generator under standard test conditions (STC): irradiance of 1000 W/m^2, module temperature 25°C and AM 1.5 spectrum [2]. Generally, the theoretical P_M^* of a PV generator is the sum of the maximum power of the installed modules under STC according to their datasheet. However, this value is an overestimating approximation since the PV generators present losses due to module mismatch and cable resistivity, among others. Therefore, it is essential to consider such intrinsic losses in the nominal power estimation since knowing its real value in operating conditions is of great interest for quality assurance of the photovoltaic plant [3]. Verifying the effectively installed P_M^* of any PV system allows identifying problems in the installation or during operation.

Following the procedure suggested by Martinez *et al*. [4], estimating P_M^* of a PV generator requires measuring the plane of array irradiance, module temperature, and DC output power. An important factor affecting the P_M^* uncertainty can be the irradiance measurement in the tilted plane of the PV generator. Using a calibrated PV module of the same technology as the PV generator as an irradiance sensor has the advantage of considering the spectral response [5], decreasing the spectral mismatch error in modelling the output power. However, installing a PV module as a sensor requires calibration in a certified laboratory with a solar simulator. Such laboratories are yet scarcely accessible in many parts of the world, particularly in developing countries.

The present work investigates the possibility of using the irradiance values from satellite-based, open-access databases, such as PVLIB [6], as an alternative to in-situ ground-based measurements. To do this, section 2 presents the PV plant under study and the experimental setup. Section 3 shows the procedure followed to calculate the nominal power using the ground sensor. Section 4 discusses the nominal power values resulting from the irradiance database in comparison to the ground measurements.

2. Experimental setup

Figure 1 shows the studied PV generator located in Granada, Spain, with a nominal power of 109.4 kW according to the manufacturer data sheet [7]. Its PV modules have a fixed tilted angle of 30° and are oriented south. The PV generator's main electrical characteristics are summarized in Table 1.
The experimental campaign took place from March to septembre 2018. Three main parameters were recorded every 30 seconds: (1) Direct Current power P_{DC} with a YOKOHAMA WT1600 wattmeter, (2) module temperature (T_m) with a PT100 sensor, and (3) ground irradiance (G_{Mod}) with a calibrated PV module.
Adittionally, PVLIB is an online database for Python developed by Sandia National Laboratories. It contains a repository with weather data to model PV systems [8] and it is comparable in quality with commercial packages such as PVsyst [9]. In this sense, the information provided by the PVlib in the irradiance values has been considered as input in the following section to calculate the nominal power.

Figure 1. View of the 109.4 kW photovoltaic generator.

Table 1. Electrical parameters of the PV generator at STC according to the manufacturer.

	Units	Value
Power at maximum power point	kW	109.4
Current at the maximum power point	A	257.6
Voltage at the maximum power point	V	574.2
Power temperature coefficient	%/°C	-0.43
Number of modules per string connected in series		18
Number of strings connected in parallel		32

3. Nominal power estimation

The total number of days during this experiment was 135. Most of the days had partially cloudy sky conditions such as the example shown in figure 2. However, to calculate the nominal power following [4], it is crucial to consider only the days with clear skies, such as shown in figure 3. This requirement is also indicated in the ASTM E2848-13 standard [10]. For our experimental campaign, 37 of the 135 days met these clear-sky conditions.

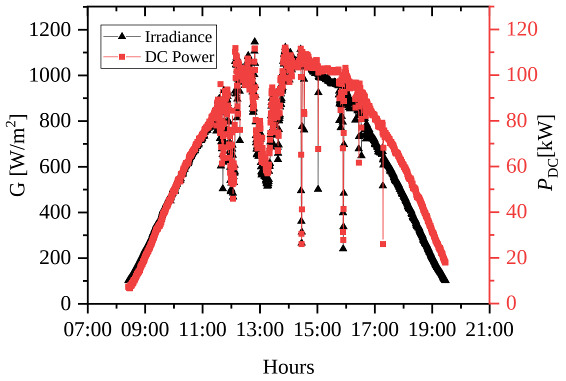

Figure 2. Exemplary, partially cloudy day (18/05/2018).

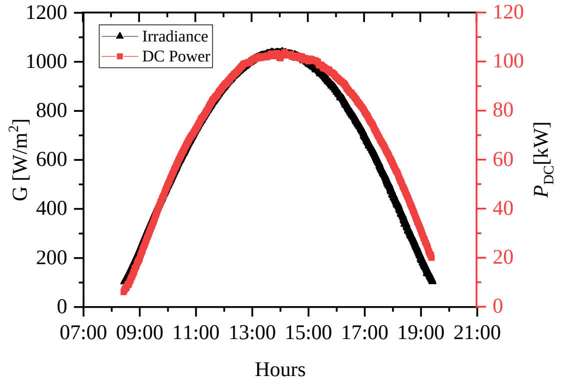

Figure 3. Exemplary, clear sky day (16/05/2018).

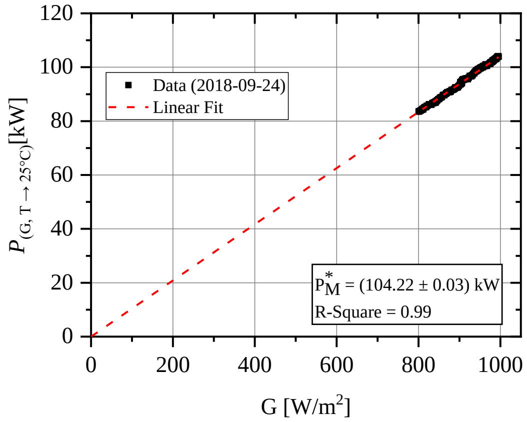

Figure 4. Linear fit of DC power corrected to 25 ºC for irradiance above 800 W/m².

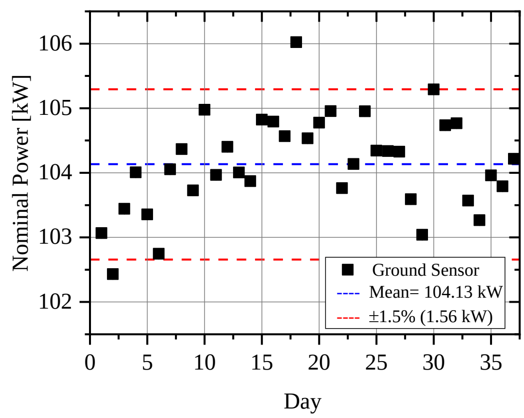

Figure 5. Calculation of the nominal power for each day in clear sky conditions.

To estimate P_M^* , the corrected DC power ($P_{T\rightarrow 25\,°C}$) is calculated using equation 1:

$$P_{T\rightarrow 25\,°C} = \frac{P_{DC}}{1 + \gamma(T_m - 25°C)} \quad (1)$$

Here, γ is the power temperature coefficient provided in the manufacturer's module datasheet, $P_{DC}$is the measured DC power and T_m the module temperature. Finally, we perform a linear fit of the data using equation 2 to obtain the nominal power P_M^* .

$$P_{T\rightarrow 25\,°C} = P_M^* \frac{G}{G^*} \quad (2)$$

Here, G^* is the irradiance under STC (1000 W/m^2), G is the plane of array irradiance. The linear fit only considers irradiance values between 800 W/m^2 and 1000 W/m^2.
Figure 4 demonstrates the resulting linear fit of the temperature-corrected DC power versus irradiance in a clear-sky day. The slope of the fit represents the nominal power. On this particular day, we obtain P_M^* = 104.22 kW. This is repeated for all 37 clear-sky days, the resulting daily P_M^* values are depicted in figure 4. The average of all values is 104.13 kW. This average P_M^* is about 5% lower than the manufacturer's total module maximum power at STC of 109.3 kW (see table 1). This difference is within

a reasonable range considering intrinsic losses and possibly degradation of the PV modules after eight years of operation [7].

4. Results and discussions

Figure 6 shows a scatter diagram of the irradiance measured with the ground sensor G_{Mod} and compared with the PVLIB G_{Lib} online database. Only clear-sky day data and irradiance values for $G_{Mod} > 100\ \mathrm{W/m^2}$ are considered here. A linear fit of the G_{Mod} and G_{Lib} data within the entire irradiance range results in a slope M =1.0289 indicating that G_{Lib} overestimates the irradiance by almost 3% on average. The relatively low spread of the data is represented with an R-squared of 0.984. We can observe several outliers [11], where G_{Lib} considerably overestimates the irradiance, possibly due to some cloud effects or shadowing of the ground sensor G_{Mod}.

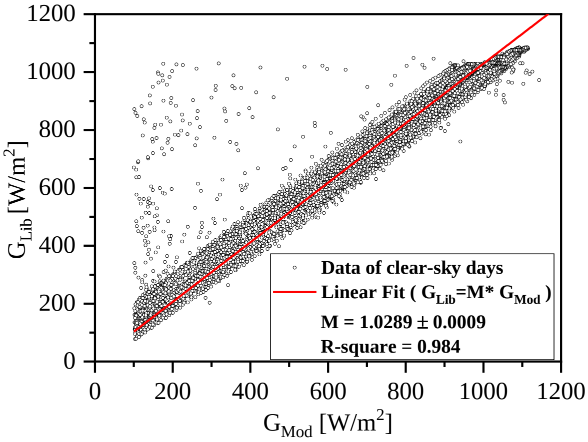

Figure 6. Scatter plot of G_{Mod} from PV module ground sensor and G_{Lib} from PVLIB database for 37 clear-sky days.

Figure 7 depicts the P_M^* estimated for both irradiance data sources on a daily basis. The estimated values resulting from the ground sensor show little variation over time in comparison to the values obtained from the PVLIB database. In the latter case, a seasonability is apparent which could be attributed to days where the irradiance is underestimated and overestimated, resulting in larger and lower P_M^*, respectively.

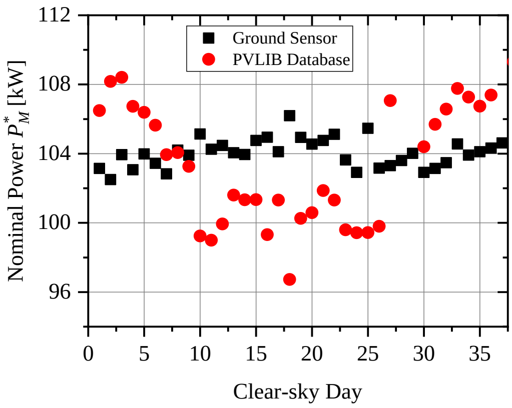

Figure 7. Nominal power for each day calculated with irradiance values using ground sensor and online database.

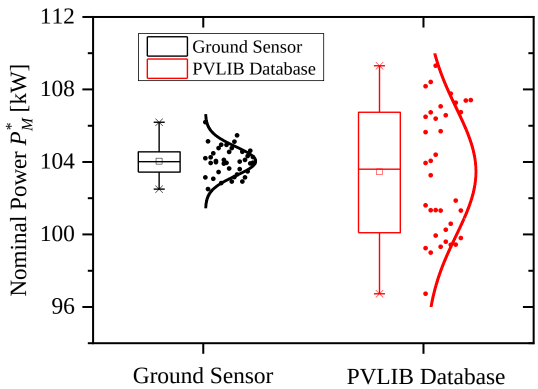

Figure 8. Boxplot analysis considering the data obtained in figure 7.

Figure 8 shows the box plot analysis for both cases. The ground irradiance sensor G_{Mod} leads to an average $P_M^* = 104.04 \pm 0.79$ kW, with error < 1%. For G_{Lib}, the estimation results in $P_M^* = 103.46 \pm$

3.5 kW, thus, with a higher relative error of about 3%. This higher error most likely originates from the over- and under estimated irradiance of the PVLIB database.
In [4], the uncertainty of calculating the nominal power in a 1.3 kW PV string is analyzed by tracing the I-V curve and following the IEC-60981 standard, resulting in 5% uncertainties. Therefore, our result in the average nominal power and the corresponding uncertainties indicate that using the PVLIB irradiance database can be a suitable alternative to using a ground sensor.

5. Conclusions

The nominal power of a photovoltaic generator in operation has been estimated. The experimental campaign was 135 days; only 37 days had clear sky conditions allowing to calculate the daily nominal power. We consider two cases: (1) ground PV module sensor G_{Mod} and (2) PVLIB database G_{Lib}. The average nominal power values were 104.04 kW and 103.46 kW for the cases (1) and (2), respectively. The main difference is evidenced in the uncertainty shown in standard deviation, which is 0.79 kW and 3.5 kW for cases (1) and (2), respectively.
Although the online irradiance database does not have the same degree of accuracy as a ground sensor, the estimated nominal power showed consistency. We can conclude that for the location of the studied PV generator using the irradiance from the PVLIB database can be a suitable alternative to in-situ ground sensor measurements. As future work, it would be important to confirm whether the methodology applying online irradiance database to estimate the nominal power can be applicable also to other locations with different climate regions.

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