Is the information provided by free satellite sources suitable for predicting or evaluating the performance of photovoltaic systems in Peru? (In memoriam to Heinrich Berg)

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Abstract. At present, there are free access online platforms that offer, free of charge, meteorological data on Peru; however, there is no study that validates the goodness of its use in the country. These types of tools are of the utmost interest, both in the design phase of photovoltaic systems PV and in the subsequent process of analysis and evaluation of their operation if it is intended to implement monitoring systems with Class B or C precision defined in the IEC 61724: 2017 standard. In this work, the consistency of the data offered by any of these platforms and their usefulness will be analysed when they are contrasted with experimental data on the operation of real systems.

1. Introduction
Photovoltaics is a fast-growing market but since the introduction of large-scale photovoltaic (PV) installations, most of them have been installed in temperate climates such as those in Europe, Japan, and North America [1]. Allowing a bigger development of the technology in these areas in compare with those where the installation of photovoltaic systems have been much less. Nevertheless, in the last years, there has been an increase of the demand for solar energy in emerging markets [2], located specially in tropical and subtropical regions. In these areas, the need arises to carry out largely amount of research to maximize the solar potential. Missing information on the exhibition of PV advances in these regions, can prompt technical dangers and negative financial effects in the execution of PV projects [3].

To assess the performance of a PV system, dependable information of the power and its behaviour under various meteorological conditions is required [4]. Solar data sources based on satellite-based estimates provide meteorological data of interest for PV systems design or operation anywhere on the world. This fact has allowed the popularization of many applications or computer platforms, both free distribution and paid, that contribute to the development of the technology worldwide.

As indicated in [5] for the case of the PVGIS platform, it is necessary to contrast the solar radiation data based on satellite images by means of comparisons with the data measured at ground level. Validation of satellite data is commonplace and numerous papers have been published dealing with data validation
for different locations around the world. In this regard, the validation of PVGIS tool satellite data can lead to overestimates of 11% and underestimates of up to 14%, depending on the locality studied [6]. However, as far as the authors are aware, no such theoretical analysis has been carried out for Peru. In this research, it is not intended to carry out a data validation study because there is not a certified laboratory for measuring surface irradiance, but what is intended is to use the data provided by the satellites to compare them with real system operation data.

With the aim of checking the correct operation of a determined photovoltaic installation using exclusively free satellite data as input parameters, a final user can use the class C monitoring system described by the standards of the International Electrotechnical Commission (IEC); the reference standard is IEC61724-1 [7]. The main objective of this work is to use free available satellite data in Peru to compare it with real data on the operation of photovoltaic systems installed in three different locations.

2. Materials and methods

2.1. Experimental setup

Within the framework of the "Emergindo con el Sol" project, three PV grid-connected systems (PVGCS) were installed in different locations in Peru with their respective monitoring systems [8]. PVGCS #1 is located at the National University of San Agustín in Arequipa, PVGCS #2 was installed at the National University of Jorge Basadre Grohmann in Tacna and PVGCS #3 is located at the National University of Engineering in Lima [9]. During the last five years, both the electrical variables and the environmental variables of interest that allow the application of the IEC61724-1 standard [7] have been measured and recorded. This standard defines three classifications - Class A, B and C - of monitoring systems based on the number of variables that must be measured in situ and the precision of the measurement. The systems defined as class B and C being those that allow the use of satellite estimates of meteorological variables.

The uncertainties and measurement errors of irradiance were mitigated as the climatic and soil effects are intrinsically considered in the estimations [10-12]. More detailed descriptions of these PVGCS, including the monitoring systems used in each, can be found in [8, 9].

2.2. Free access satellite sources

To develop this research, in the first place, it is necessary to identify the free access satellite sources that allow obtaining meteorological variables of interest for compliance with the norm in Peru. Firstly, The NASA POWER Data Access Viewer, through the SSE-Renewable Energy option, provides accumulated daily data of precipitation, ambient temperature, wind speed and incident global radiation on a horizontal surface. Secondly, Through NASA's MERRA-2 atmospheric reanalysis product, data on ambient temperature, wind speed, precipitation and incident global radiation on a horizontal surface are obtained for different temporal resolutions. Both platforms offer estimated solar data with a delay of only two days. Finally, The National Renewable Energy Laboratory (NREL) provides data on precipitation, ambient temperature, wind speed, global radiation, direct radiation, and incident diffuse radiation on a horizontal surface for full years and for different temporal resolutions. Although there are different free access satellite services for Peru, all of them provide the data offered by NASA. Therefore, the only tool available to Peru that offers free daily data is that of NASA, which because it is free is the one that could be available to a greater number of users and the one used for this research.

2.3. Mirror PV system

The method used to obtain the results of this research is based on the philosophy of the mirror or digital twin system that simulates the behaviour of the experimental installation with the difference that the environmental parameters used as input come from free satellite estimations. Thus, the mirror PV system is a class C monitoring system.

The mirror PV system is nothing more than a deterministic model of the real operation of the experimental PV installation. A grid-connected photovoltaic system, like any other engineering system, can be modelled with different levels of complexity, such as a mathematical model of constant
coefficients. Daily and monthly performance metrics for both experimental and simulated systems were calculated for the three PVGCS under study, as recommended in the IEC61724-1 standard [7]. Performance ratio (PR) was calculated for the PV installations in Arequipa and Tacna. Whereas DC performance ratio (PR\textsubscript{DC}) was calculated for the PV installation in Lima.

The simulated performance ratio (PR\textsubscript{sat}) and the simulated DC performance ratio (PR\textsubscript{DC,sat}) are given by the following equations:

\[
PR\textsubscript{sat} = \frac{Y_{f,exp}}{Y_{r,sat}} = \frac{E_{out,exp}}{P_0} \frac{P_0}{H_{i,sat}} \frac{H_{i,sat}}{G^*} = \frac{E_{A,exp}}{P_0} \frac{P_0}{H_{i,sat}} \frac{H_{i,sat}}{G^*} \quad (1)
\]

\[
PR\textsubscript{DC,sat} = \frac{Y_{A,exp}}{Y_{r,sat}} = \frac{E_{A,exp}}{P_0} \frac{P_0}{H_{i,sat}} \frac{H_{i,sat}}{G^*} \quad (2)
\]

Where \(Y_{f,exp}\) (Wh·W\(^{-1}\)) is the experimental final yield of the PV system, \(Y_{r,sat}\) (Wh·W\(^{-1}\)) is the reference yield obtained from the satellite data, \(E_{out,exp}\) (Wh) is the experimental AC output energy of the photovoltaic system, \(P_0\) (W) is the PV system rating, \(H_{i,sat}\) (Wh·m\(^{-2}\)) is the in-plane irradiation obtained from the satellite data, \(G^*\) (W·m\(^{-2}\)) is the reference in-plane irradiance (1000 W·m\(^{-2}\)) at which \(P_0\) was determined, \(Y_{A,exp}\) (Wh·W\(^{-1}\)) is the experimental PV array energy yield and \(E_{A,exp}\) (Wh) is the experimental DC energy of the PV array.

The experimental performance ratio (PR\textsubscript{exp}) and the experimental DC performance ratio (PR\textsubscript{DC,exp}) are calculated as follows:

\[
PR\textsubscript{exp} = \frac{Y_{f,exp}}{Y_{r,exp}} = \frac{E_{out,exp}}{P_0} \frac{P_0}{H_{i,exp}} \frac{H_{i,exp}}{G^*} \quad (3)
\]

\[
PR\textsubscript{DC,exp} = \frac{Y_{A,exp}}{Y_{r,exp}} = \frac{E_{A,exp}}{P_0} \frac{P_0}{H_{i,exp}} \frac{H_{i,exp}}{G^*} \quad (4)
\]

Where \(Y_{r,exp}\) (Wh·W\(^{-1}\)) is the experimental reference yield and \(H_{i,exp}\) (Wh·m\(^{-2}\)) is the experimental in-plane irradiation.

For the performance metrics calculations, only days have been studied in which it is considered that the operation has been perfect and that there have been no problems either with the operation of the system itself or with the measurement.

\[\text{Figure 1. Diagram of the methodology used in the study, differences between the performance ratio obtained from the class C mirror PV system and the performance ratio obtained from the class B experimental monitoring system.}\]

Two statistical metrics were applied to evaluate the goodness of the afore-mentioned methodology. The root mean square error (RMSE) provides information on the dispersion of the mirror or digital twin
system performance metrics with respect to the experimental measurements. Whereas the mean bias error (MBE) displays the under or over estimation of simulated values.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (PR_{sat_i} - PR_{exp_i})}{n}} \quad (5) \\
MBE = \frac{\sum_{i=1}^{n} (PR_{exp_i} - PR_{sat_i})}{n} \quad (6)
\]

Where \( PR_{sat_i} \) and \( PR_{exp_i} \) represent the i-th value of the estimated and measured performance ratio, respectively, and \( n \) is the number of values considered during the period (day or month).

3. Results and discussion
The energy characterization of the three PVGCS studied will be presented in this section using exclusively as input the free satellite data offered by NASA. The results obtained will be compared with the experimental measures of operation of the systems during the period under scrutiny. For the PV installation located in Arequipa the period under study was from August 2015 to December 2020, for the one installed in Tacna was from May 2015 to December 2019 and for the PV system in Lima was from July 2016 to June 2018. There has carried out also a daily comparison between the performance metrics, considering for each of the PV installations a perfect summer month with 31 days of complete data and a winter month with the same conditions.

3.1. Monthly analysis
Figures 2-4 represent the comparison between the estimated and measured values of \( PR \) for the PVGCS located in Arequipa and Tacna and the comparison between the estimated and measured values of \( PR_{DC} \) for the grid-connected photovoltaic system in Lima.

![Figure 2](image_url)

**Figure 2.** Variations between the experimental \( PR \) values and the \( PR \) values obtained from the mirror PV system for PVGCS #1 over the period under study.
In table 1, it is summarized the monthly values of the calculated parameters RMSE and MBE for all the period under study. For the three PVGCS, high values of RMSE and MBE are presented, being the PV system in Arequipa the one which presents the lowest values and the installation in Lima the one which presents the highest values.

|       | RMSE (%) | MBE (%) |
|-------|----------|---------|
| Arequipa | 11.80    | 9.55    |
| Tacna    | 16.59    | 15.33   |
| Lima     | 32.10    | 28.86   |

3.2. *Daily analysis*

To do a daily analysis, for each of the PV installations a perfect summer month with 31 days of complete data and a winter month with the same conditions have been considered. High values of RMSE and MBE are also presented as in the monthly analysis. Being the installation in Arequipa the one who has the lowest values and the one in Lima which presents the highest values. Table 2 presents the results for the analysis carried out for both the summer and the winter month.
input data the data tend to overestimate the solar resource and, in consequence, would be to have a network of certified weather stations that would allow the data provided by satellite sources. Satellite data tend to overestimate the solar resource and, in consequence, the real global performance of the three photovoltaic systems tend to decrease. Although this is a first approximation study and its results should not be considered definitive, Henrich Berg was right when he stated that it was necessary to be cautious when using satellite data for the estimation and supervision of systems in Peru. This is the first-time experimental operation data has been compared with estimated satellite data so further research is needed, and it seems that the next step would be to have a network of certified weather stations that would allow the data provided by satellite to be cross-checked with ground data.

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### Table 2. Daily summer and winter values of RMSE and MBE for the three PV systems under study.

|        | Summer | Winter |
|--------|--------|--------|
|        | RMSE (%) | MBE (%) | RMSE (%) | MBE (%) |
| Arequipa | 14.01 | 12.01 | 14.27 | 14.12 |
| Tacna   | 20.79 | 19.74 | 24.89 | 8.23 |
| Lima    | 21.68 | 16.24 | 42.81 | 33.13 |

### 4. Conclusions

The energy characterization of these photovoltaic systems using exclusively as input data the meteorological variables offered by free satellite services in Peru, brings out notable discrepancies in compare with the experimental measures of operation of the PV systems during the period under study. Therefore, for none of the different locations considered in this study is recommended the prediction or evaluation of the performance of photovoltaic systems using the information provided by satellite sources. Satellite data tend to overestimate the solar resource and, in consequence, the real global performance of the three photovoltaic systems tend to decrease.