Report on Round-Robin test of calibration accuracy for different methods and sites

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1 Introduction

Solar radiation resource assessment is crucial for potential solar power plant sites. Site selections with inadequate resource assessment could result in complete economic project failures. Accurate solar resource data can be gathered by thermopile based sensors like pyrheliometers for direct normal irradiance measurements (DNI) and pyranometers for direct global and diffuse horizontal irradiance measurements (GHI and DHI respectively) as specified in [ISO 9060]. Pyrheliometers and pyranometers used for DHI measurements require a sun tracker which follows the course of the sun. The correct alignment of the sensors on the tracker and the tracker itself is essential. Usable data can only be obtained, if a periodic and frequent cleaning procedure of the sensors is guaranteed [Geuder, Quaschning, 2006]. This maintenance demand could cause increased cost especially for remote locations.

Semiconductor based Rotating Shadowband Irradiometers (RSI), which measure DNI, GHI and DHI are less affected by soiling [Geuder, Quaschning, 2006] and do not require a solar tracker. Furthermore, a small PV solar panel is sufficient for the electrical supply of a RSI. Thus RSI are the preferable choice for long term measurement campaigns on remote sites where daily cleaning is not feasible, despite their lower accuracy when compared to well-maintained thermopile based sensors.

However, a thorough calibration is required which must consider also the correction function for systematic errors caused by its spectral non-uniform responsivity, cosine-response as well as temperature effects. The needed calibration procedures developed by DLR were investigated as part of the WP 11 task 1 of SFERA II project. All results of this work are stated in [Jessen et al., 2017]. This work is related to the influence of the calibration site on the calibration results. For this purpose a round robin test is conducted calibrating a single RSI according to different methods described in [Jessen et al., 2017] at the Plataforma Solar the Almeria (PSA) and at an additional CIEMAT test site facility in Madrid. [Jessen et al., 2017] showed that the calibration results depend on the chosen data duration and the time of the year. Therefore the same period over the year was chosen for both sites:

- PSA: 15.07.2015 – 06.01.2016
- Madrid: 15.07.2016 – 06.01.2017

Except of effect caused by the minor latitude deviation and the temporal distribution of cloudiness between both sites, this selection helps to archive that these data sets contain similar sun angles.

This report presents the results of both sites for different calibration procedures and discusses the possible reasons for any detected deviations. After a short description of the calibration setups in section 2, the evaluation method is described in section 3. Then results are presented in section 4 and finally conclusions are summarized.

2 Calibration facilities

The commonly used RSI model RSP4G from Reichert GmbH (see **Figure 1**) was chosen as the test instrument for this work. It uses a LI-200 Licor Si-pyranometer. The shadow band rotates once per minute and shades the pyrometer.

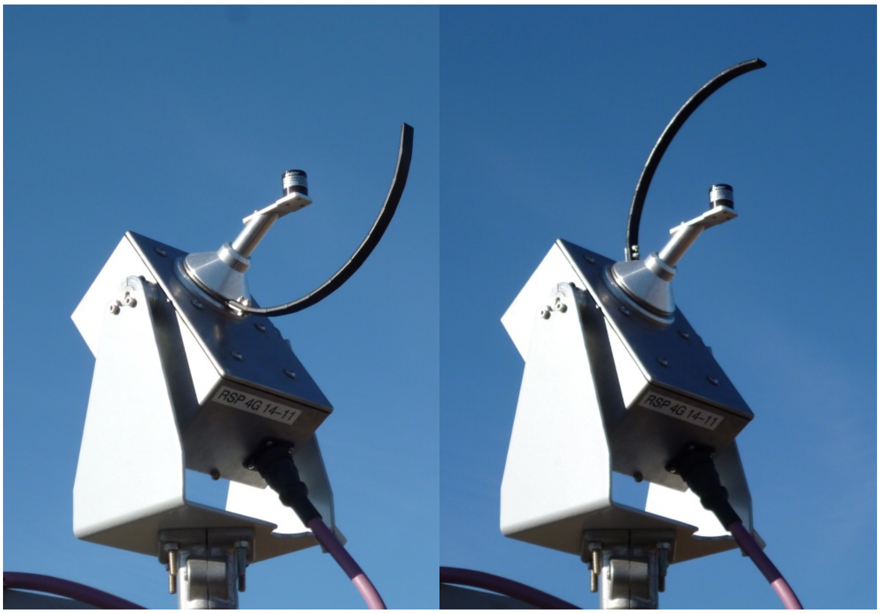

Figure 1. RSP4G RSI model left: resting position (GHI measurement) right: rotation (DHI measurement)

During the rotation period the data resolution is increased massively to the so called burst. When the pyranometer is shaded the DHI is recorded, during the remaining unshaded times the GHI is recorded. The DNI is calculated by the DHI and GHI signal and the sun zenith angle (SZA).

Equation 1

$$DNI = \frac{GHI - DHI}{\cos(SZA)}$$

In both sites similar thermopile based sensors consisting of one tracked pyrheliometer (DNI) and pyranometer (DHI) and an additional unshaded pyranometer (GHI) are used as reference sensors. All reference sensors had a valid calibration according to the ISO standards 9059, 9846 and 9847.

Irradiance data from the RSI and the reference sensors are logged as 1 minute and 10 minutes averages via a Campbell Scientific CR 1000 datalogger. The precise site locations and involved main hardware components are listed in Table 1. Figure **2** illustrates the test facilities.

Table 1. **Precise test site locations and involved main hardware during the calibration campaigns**

	PSA	Madrid
Latitude	37°5'27.02''N	40°27'21.60''N
Longitude	2°21'29.18''W	3°43'48.00''W
Altitude	495 m	650 m
Test RSI	RSP 4G 09-18 with PY-60281	RSP 4G 09-18 with PY-60281
Tracker	Black Photon Sunscanner SC-002	Geónica SunTracker-2000 (SN159)
Reference pyrheliometer (DNI)	CHP1 090163 (7.98 µV/(W/m²))	CH1 40381 (10.87 µV/(W/m²))
Reference pyranomtere (GHI)	CMP21 090281 (9.47 µV/(W/m²))	Hukseflux SR12 1185 (13.64 µV/(W/m²))
Reference pyranomtere (DHI)	CMP21 090292 (8.30 µV/(W/m²))	Hukseflux SR12 1182 (12.39 µV/(W/m²))
Data logger	Campbell CR1000 (sn. E-7164 (for reference signals) and sn.E-11375 (for RSI))	Campbell CR1000 (sn. E-13886 (for reference signals and RSI))

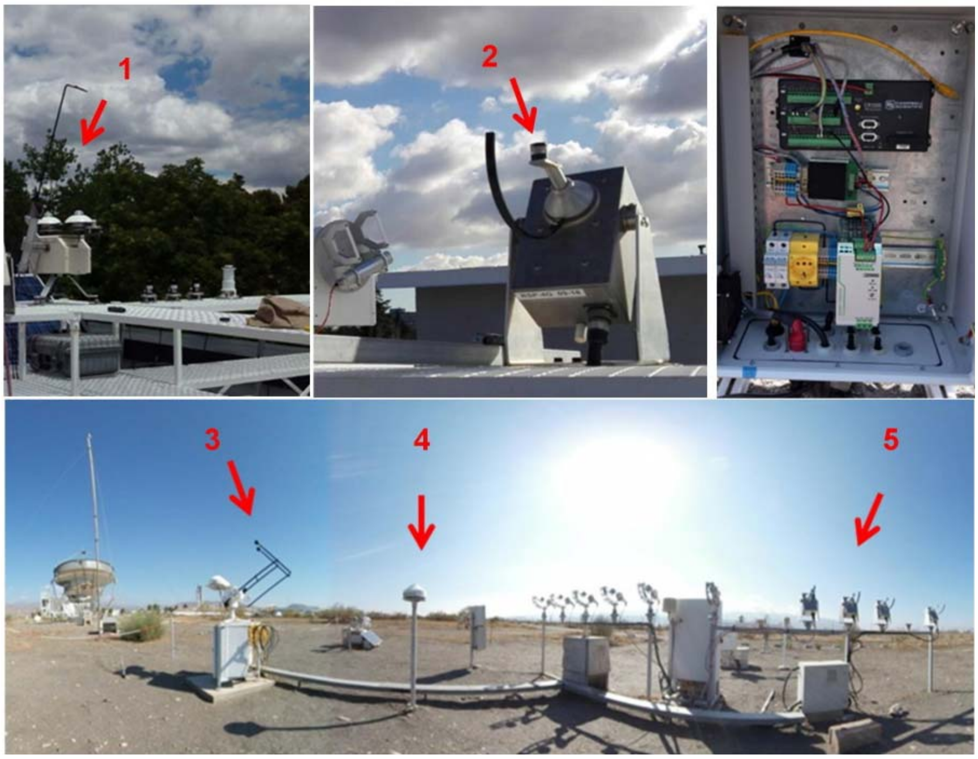

Figure 2. **Top left) Madrid calibration setup (1: Tracker with reference sensors and 2: mounted RSI); Top right) Data acquisition system used in Madrid setup; bottom) PSA test setup (3: Tracker with reference DNI and DHI measurement, 4: GHI measurement for quality check of reference data and 5: RSI test bench)**

3 Calibration execution and evaluation method

As shown by [Jessen et al., 2017], the chosen data duration and corresponding time of the year has a certain impact on the calibration results. In order to minimize these effects, the calibration was carried out in the same time range in consecutive years for both sites.

- PSA: 15.07.2015 – 06.01.2016
- Madrid: 15.07.2016 – 06.01.2017

Despite minor latitude deviations and distributions of unuseable data due to high cloudiness this selection achieves a similar range of sun angles (see Table 2).

Table 2. **Sun angle range during calibration period**

	PSA	**Madrid**
Sun azimuth range 15.07.2015/2016	63° to 297°	61° to 299°
Sun azimuth range 21.12.2015/2016	120° to 240°	123° to 237°
Max sun elevation at solar noon 15.07.2015/2016	74°	71°
Min sun elevation at solar noon 21.12.2015/2016	29°	26°

Two distinguished calibration procedures are carried out. Only a short description of the different procedures will be presented in this report, detailed descriptions are stated in another SFERA II WP 11 task 1 Report [Jessen et al., 2017]. All procedures determine calibration factors by comparing the reference irradiation data with the corresponding RSI data.

- DLR-VigKing
    - The correction functions presented in [Vignola et al., 2006] & [Geuder et al., 2011] are applied to the data.
    - Three separate calibration factors for the GHI, DHI and DNI are determined by minimizing the root mean square deviation (rmsd) (see Equation 3) of the corresponding RSI signal to the reference signal.
- DLR-2008
    - The correction functions presented in [Geuder et al., 2008] are applied to the data.
    - Two separate constant calibration factors for the GHI and DHI are determined by minimizing the rmsd of the GHI and DNI to the reference signals. No

specific DNI calibration factor is determined

All methods are applied on 10 minute average data. For the calibration only the relevant operation range of solar thermal power plants are considered with:

- DNI > 300 W/m²
- GHI > 10 W/m²
- DHI >10 W/m²
- Sun height angles > 5°

Outliers with deviations of more than 25% are not considered. All data are also screened and filtered manually to ensure the required high quality of the data by excluding erroneous measurements. The resulting effective calibration period is listed in Table 3. The more urban environment in Madrid with partial influences from neighboring buildings and large trees (shading and reflexes), especially during the winter time with lower sun angles, led to a stronger filtering of the data.

Table 3. **Effective calibration period (used time resolution: 10 minute average)**

	PSA	**Madrid**
Effective period GHI	1533 h	1340 h
Effective period DHI	1535 h	1341 h
Effective period DNI	1146 h	831 h

The quantitative distribution of the used data (already filtered) is illustrated in Figure **3**, Figure **4** and Figure **5**.

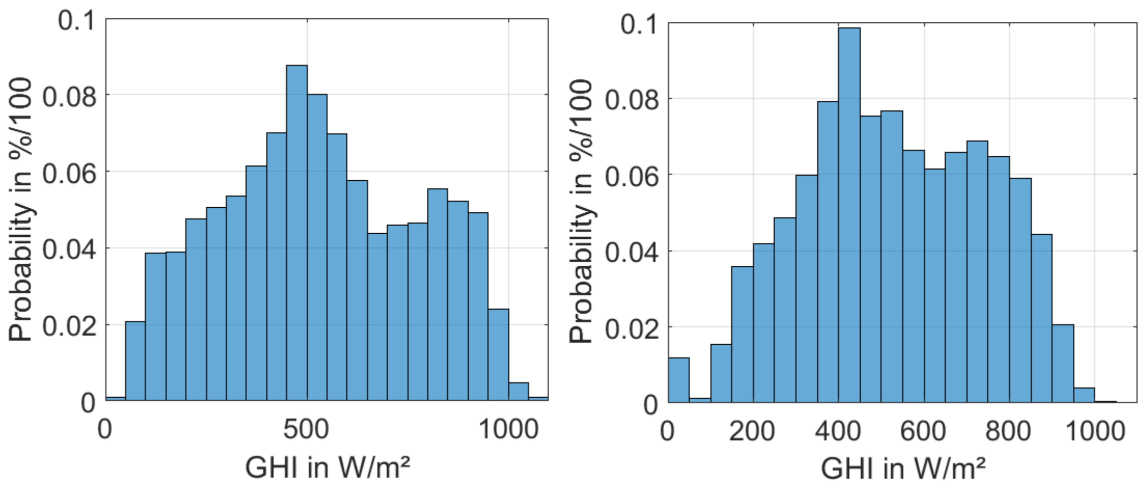

Figure 3. **Histogram GHI reference data (left PSA and right Madrid)**

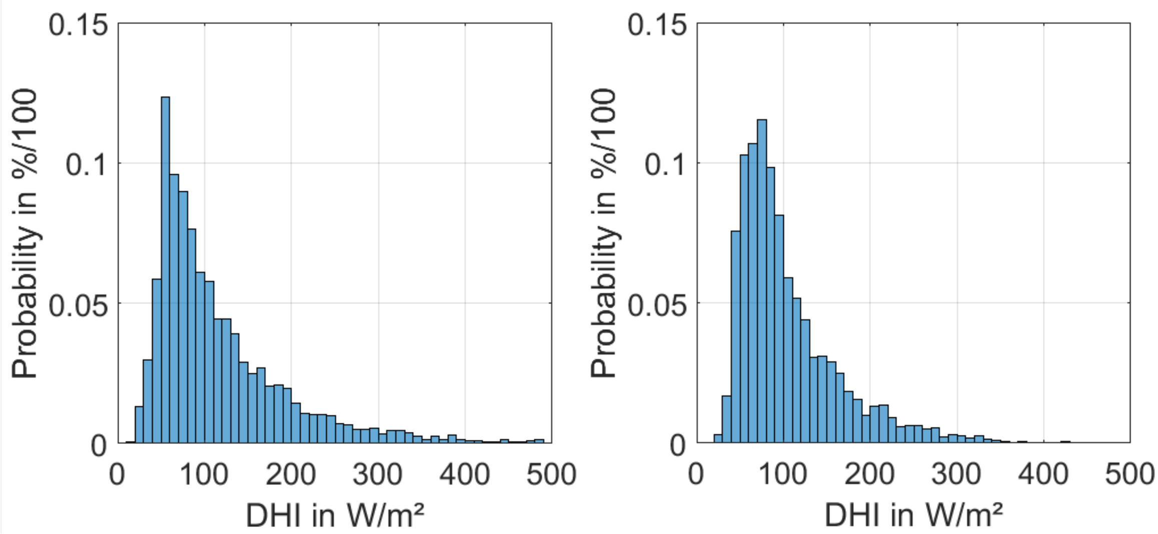

Figure 4. **Histogram DHI reference data (left PSA and right Madrid)**

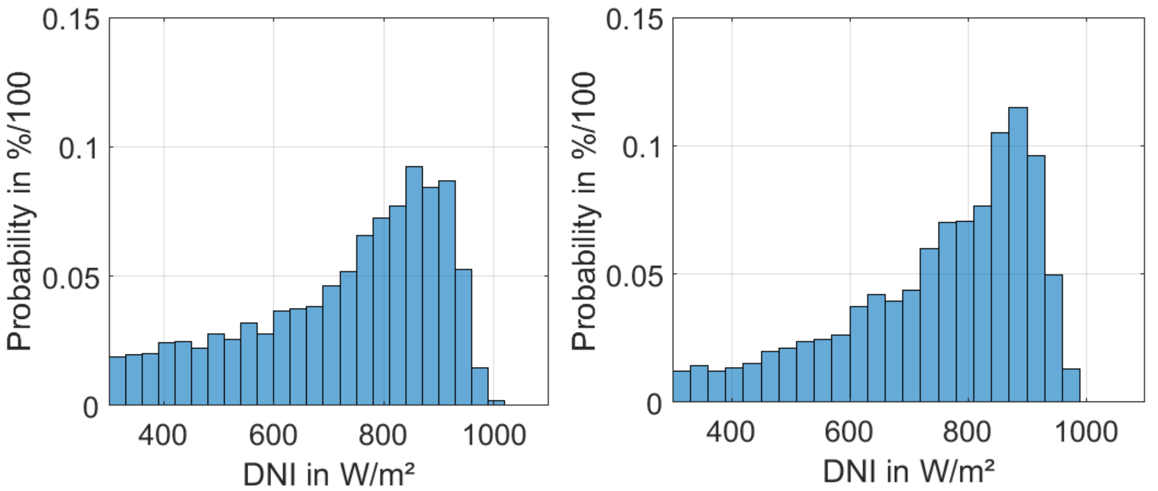

Figure 5. **Histogram DNI reference data (left PSA and right Madrid)**

4 Results

The bias, the standard deviation (std) and the rmsd are calculated for the DNI, GHI and DHI for both sites and both calibration procedures, as defined in Equation 2, Equation 3 and Equation 4. N is the total number of valid readings, T_i as the irradiance reading of the test sensor, R_i as the irradiance reading of the reference sensor and $\bar{T}$ and $\bar{R}$ as the average observed irradiance of the test and reference sensor, respectively.

Equation 2 $$bias = \frac{1}{N}\sum_{i=1}^{N} T_i - R_i$$

Equation 3 $$std = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(T_i - R_i - (\bar{T} - \bar{R}))^2}$$

Equation 4 $$rmsd = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - R_i)^2}$$

Table 4 list all statistical results. No significant deviation between both calibration procedures are observed in the case of the PSA. Std and rmsd values lay around 5 to 6 W/m² for the DHI and GHI and around 10 to 11 W/m² for the DNI, which corresponds to a rather better than average calibration result for a RSP4G RSI model. In the case of the Madrid site no significant deviations are observed in between both procedures for the GHI and DHI with std and rmsd values around 9 to 11 W/m² and 4 to 5 W/m². Things are different with the DNI, where larger deviations are observed in-between the procedures. The DLR-VigKing procedure shows std and rmsd values around 22 W/m² the better outcome compared to std and rmsd around 27 W/m² for the DLR2008 procedure. The rmse found for PSA are smaller than usual, while those for Madrid are approximately 5 to 10 W/m² higher than what is typically found during calibrations. Relative to a DNI of 1000 W/m² the rmse represent about 1.1% for PSA and about 2.5 % for Madrid.

Table 4. **statistical results of calibration procedures**

PSA before calibration			
	GHI	DNI	DHI
Bias in W/m²	-19.9	9.1	-20.9
STD in W/m²	10.5	15.8	10.0
RMSD in W/m²	22.5	18.2	23.2
PSA DLR-VigKing after calibration			
	GHI	DNI	DHI
Bias in W/m²	-0.2	0.2	0.1
STD in W/m²	6.1	10.4	5.2
RMSD in W/m²	6.1	10.4	5.2
PSA DLR2008 after calibration			
	GHI	DNI	DHI
Bias in W/m²	-0.9	-1.1	-1.0
STD in W/m²	5.3	11.1	5.3
RMSD in W/m²	5.4	11.2	5.4

Madrid before calibration			
	GHI	DNI	DHI
Bias in W/m²	-22.3	-5.8	-19.3
STD in W/m²	13.5	25.4	9.7
RMSD in W/m²	26.1	26.0	21.6
Madrid DLR-VigKing after calibration			
	GHI	DNI	DHI
Bias in W/m²	1.3	0.9	0.5
STD in W/m²	9.1	22.3	4.5
RMSD in W/m²	9.2	22.3	4.5
Madrid DLR2008 after calibration			
	GHI	DNI	DHI
Bias in W/m²	0.1	-2.2	-0.9
STD in W/m²	10.8	27.5	5.0
RMSD in W/m²	10.8	27.1	5.1

As stated previously separate calibration factors for the GHI, DHI and DNI are determined in the case of DLR-VigKing where in the case DLR-2008 this is done only for the GHI and DHI. This might be an advantage of the DLR-VigKing procedure compared to the DLR2008 procedure, especially in cases of more profound fluctuation of the DNI deviation between the test and reference sensor. From the scatter plots shown in Figure **6** it can be seen that the RSI DNI measurements and reference DNI measurements are in general less scattered for the PSA site, which might explain why the deviations in between the procedures are not as profound, but also why the overall rmse values are lower compared to the Madrid site. The reasons for this observation might be the more urban environment of the Madrid site with stronger disturbances or sensor alignment/tracking imperfections which only cause small deviations in DHI and GHI, but higher deviations for the calculated DNI.

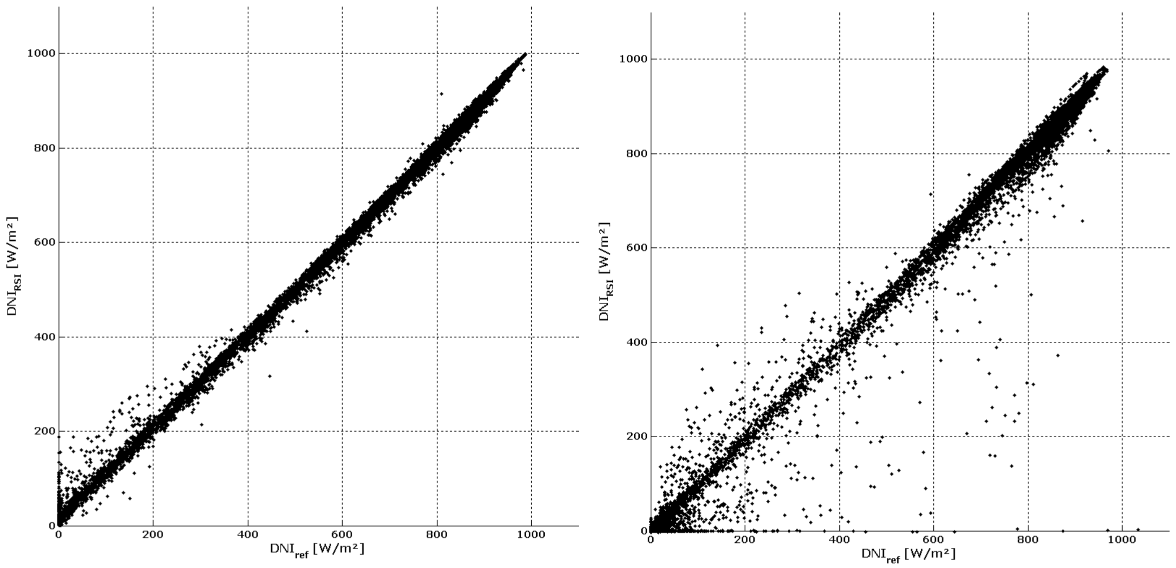

Figure 6. **Scatter plots corrected DNI_{RSI} (DLR-VigKing) over DNI_{ref} (left PSA and right Madrid)**

5 Conclusion

Ciemat and DLR implemented two RSI calibration facilities located at the PSA and the rooftop of a Ciemat facility in Madrid. Two calibration campaigns with the same RSP4G RSI were performed successively at both sites. In order to reduce seasonal dependences , the calibration campaigns were carried out in the same time range in consecutive years for both sites.

- PSA: 15.07.2015 – 06.01.2016
- Madrid: 15.07.2016 – 06.01.2017

The two distinct calibration procedures DLR-VigKing and DLR-2008 are applied on the data sets. The PSA calibrations show lower overall deviation for the DNI with a rmsd of 10.4 W/m² (VigKing) to 11.2 W/m² (2008) compared to the Madrid site with an rmsd of 22.3 W/m² (VigKing) to 27.1 W/m² (2008). Stronger fluctuations are observed in the comparison of the corrected RSI DNI to the corresponding reference DNI at the Madrid site, which could explain the better results achieved at the PSA. In consideration of a DNI value around 1000 W/m², would the observed rmsd values correspond to a relative rmsd between 1 to 3 % of the considered value.

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PSA	Plataforma Solar de Almería
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
DHI	Diffuse Horizontal Irradiance
rmsd	root mean square deviation
std	Standard deviation