ENERGY PERFORMANCE RESULTS OF 240 MW X YEAR OF SPANISH LARGE-SCALE PV PLANTS

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ABSTRACT: In this paper, the performance of several large-scale Spanish photovoltaic plants is presented. 20 installations, totalling more than 90 MW, are analysed for a period of up to 4 years. We suggest a procedure to assure the consistency of the data coming from the field and a method of calculating the energy availability rate of the installations, both of them in a way that is independent of the operator of the plant. The operational results are final yields of more than 1,500 kWh/kW for static installations and more than 2,100 kWh/kW for a 2-axis tracking configuration; average performance ratios of 0.8 and energy availabilities of more than 99.5%, with no significant differences between static and tracking systems. Because of the large size and wide location distribution of this sample, we consider these results representative of the performance of large scale PV plants in Spain.
Keywords: Energy production; field performance; performance ratio; energy availability; large grid-connected PV plants

1 INTRODUCTION

This paper reports on the operational results of several large-scale photovoltaic (PV) plants currently in operation in Spain. Up to now, numerous reports have been published assessing the performance of PV installations. They have mainly analysed small installations, both for demonstration [1-3] or commercial purposes [4-12]. The analyses of large-scale commercial PV plants have basically focussed on single installations [13-15]. However, detailed information on their performance is still scarce [16]. In this article, the performance of 20 multi-megawatt plants, totalling 90 MW, is considered for a period of up to 4 years.

All of the analysed plants were built under a financial scenario, defined by the RD-661/2007 feed-in tariff (today revoked), that led to the installation of nearly 3 GW in 2008. This law stated a sharp decrease in the feed-in tariff for installations of more than 100 kW. This led all the plants to be made up of legally independent 100 kW units, each of them with its correspondent energymeter for billing purposes. Figure 1 shows the electric layout of this configuration. It has allowed us to work with several units in each plant and thus, quantify not only the annual production and PR, but also the energy availability in a way that is independent of the operator data. The underlying idea is that, because the operating conditions are the same, the 100 kW PV plants are expected to produce at a similar rate. Thus, any performance anomaly is detected and quantified, in terms of energy losses.

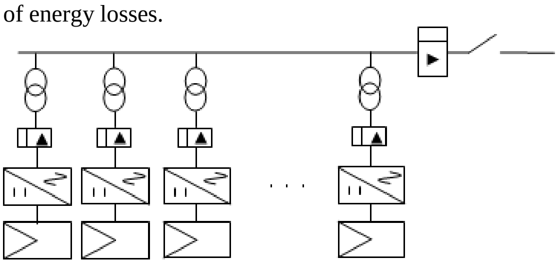
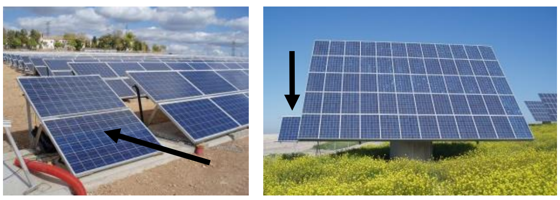


Figure 1. Electrical scheme of the analysed plants: 100 kW generator units, each of which feeding an inverter and then a low-to-medium voltage transformer, and controlled by means of an energymeter.

The Solar Energy Institute of the Polytechnic University of Madrid (IES-UPM) has been involved in the quality control process of several plants, up to a total of 300 MW, carrying out quality control analysis at two moments: at the reception of the plant (the beginning of its operation) and after one or two years of functioning. The aim of the former is to check the energy production capacity of the installation, by comparing its real production for one week with respect to that estimated from the operating conditions, i.e. the in-plane irradiance, $G(\mathrm{I})$, and the cell operation temperature, T_C; and to test the real behaviour of the different components of the plant: generator, inverter, trackers, etc [17-18]. The objective of the latter is to control the energy availability during the period under consideration, using the operating condition data recorded by a meteorological station and the data from the energymeters, as a measure of its reliability and the quality of its operation and maintenance procedures. This test is based on the meteorological and operating conditions and the production data coming from the field. Depending on the different contractual agreements, the IES-UPM now possesses detailed performance data from one to four years.

As a part of the reception tests carried out by the IES-UPM, every plant is equipped with reference modules for measurement of the operating conditions, $G(\mathrm{I})$ and T_C, using the short-circuit current and open-circuit voltage, respectively [19,20]. These modules were previously stabilized and calibrated at the IES-UPM facilities, and then installed in the corresponding generator structure in a place free from shadows. The traceability of these modules is referred to the CIEMAT and they are recalibrated biannually. Figure 2 shows a couple of examples of reference modules. Furthermore, there is a standard meteorological station that measures horizontal irradiance, $G(0)$, ambient temperature, T_A, and wind speed, S_W. This meteorological station also collects the data from the reference modules. As these data are somewhat redundant, their combination allows us to check their validity.

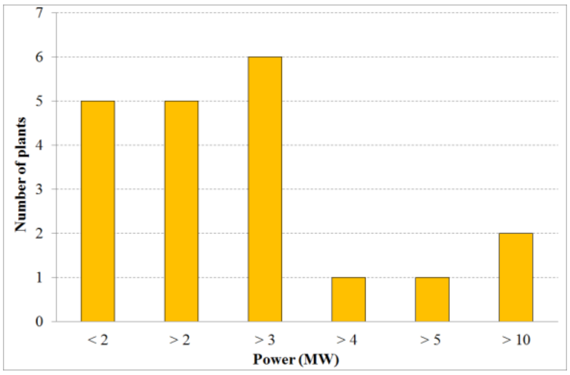


(a) (b)

Figure 2. Example of reference modules installed in a (a) static and a (b) 2-axis tracking configuration.

Depending on the kind of work carried out by the IES-UPM in each of the 20 installations studied, data is available from 1 to 4 years, up to a total of 240 MW·year. Figure 3 shows the distribution of the plants within the Iberian Peninsula and the first 4 columns of table 1 present their main characteristics.

(a)



(b)

Figure 3. (a) Geographic distribution of the analysed plants. Squares represent static configuration installation; triangles, 2-axis tracking configuration with horizontal primary axis; and circles, 2-axis tracking configuration with vertical primary axis. The size of the plant is proportional to the symbol area. (b) Peak power distribution of the analysed installations.

First, a procedure is presented to deal with the data coming from the field, for assuring its consistency. Then, the main analysis parameters are specified. In particular, a method for calculating the energy availability of a PV plant is described. Finally, the main results are discussed.

2 DATA CONSISTENCY

For each month and given plant we receive the 10-minute average records of the meteorological ($G(0)$,T_A, and S_W provided by the meteorological station) and operating ($G(I)$ and T_C given by the reference modules) conditions, and the monthly production of all the 100 kW units (given by the billing energymeters). The ambient and operating conditions are measured once a minute and their corresponding mean recorded 10-minute intervals. The operation and maintenance data consistency is analysed by comparing certain combinations of these data with previously known values. In particular, two of them are considered: the Nominal Operation Cell Temperature (*NOCT*) and the relationship between the incident irradiation gains at the generator tilt angle with respect to the horizontal irradiation.

2.1 NOCT

For moderate winds, there is a linear relationship between $T_C - T_A$ and $G(I)$, as described by equation (1):

$$T_C - T_A = m \cdot G(I) \qquad (1)$$

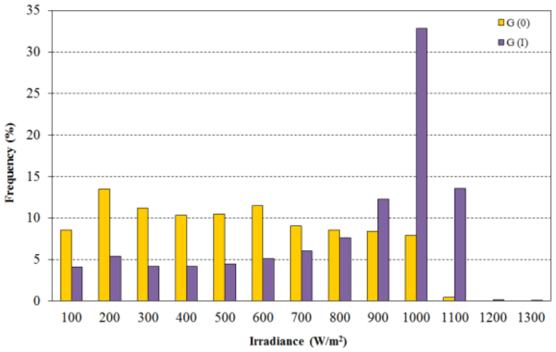
where the value of *m*, which is a characteristic of the type of PV module is derived from the concept of the Nominal Operation Cell Temperature (*NOCT*) by means of:

$$m\ (^{\circ}Cm^2/W) \approx \frac{NOCT(^{\circ}\mathrm{C}) - 20\ (^{\circ}C)}{800\ (W/m^2)} \qquad (2)$$

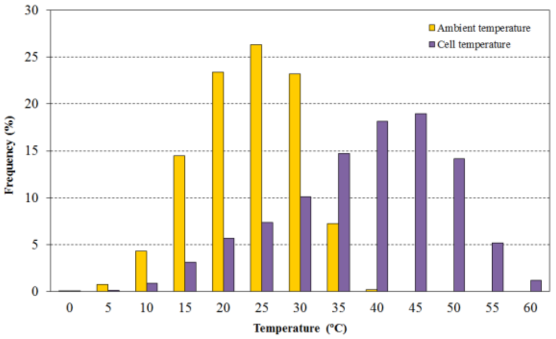
NOCT is defined as the temperature reached by the open circuited cells in a module mounted on a structure with a 45º tilt angle and the rear side open and under the following conditions: 800W/m^2 of irradiance on the cell surface, $G(I)$, 20°C of air temperature, T_A, and 1m/s of wind speed, S_W. The IEC-61215 describes both the procedure and the requirements for measuring the *NOCT*, such as installing the anemometer at 0.7 m above and 1.2 m to the west or to the east of the upper part of the modules; or considering only the moments with $G(I) > 400$ W/m^2, 5 ºC < T_A < 35 ºC and 0,25 m/s < S_W < 1,75 m/s [21]. In accordance with these conditions, the manufacturer provides a reference $NOCT_{MNF}$ value with typically a ±2 ºC uncertainty. From our in-the-field data, we plot the 10 minutes means of $T_C - T_A$ versus $G(I)$ (once filtered by the $G(I)$, T_A and the aforementioned S_W conditions), which allows experimentally a *NOCT* value ($NOCT_{EXP}$) as to be calculated as:

$$NOCT_{EXP}\ (^{\circ}\mathrm{C}) \approx 20\ (^{\circ}C) + m_{EXP}\ \ (^{\circ}Cm^2/W) \times 800\ (W/m^2) \qquad (3)$$

where m_{EXP} is the slope of the best fit linear adjustment of the plot. Then, $NOTC_{EXP}$ can be compared with $NOTC_{MNF}$. This procedure allows the $NOCT_{EXP}$ to be estimated but, as some of the conditions established in the norm are not fulfilled when measuring in the field (neither the position of the anemometer nor the tilt angle of the modules usually coincide with the requirements), it entails a wider range of uncertainty (that we have estimated as ±5 ºC), even for periods with no anomaly. Hence, the key idea is that errors in the data acquisition process generate deviation in the $NOCT_{EXP}$ greater than that margin. Figures 4 and 5 show an example of this exercise for the Cádiz-2 PV plant. This installation is located at 36.76 ºN and 6.32 ºW and its weather and operating conditions are shown in figure 4. Figure 5 shows the $NOCT_{EXP}$ calculated every hour for the first six months of 2010, where the spread the trend is caused mainly by the effect of the wind, while the existence of some outliers (especially those greater than the trend line) is a result of the effect of shadows: the current generated by a photovoltaic module reacts instantaneously to a variation in the irradiance but it takes several minutes to become thermally stabilized, thus leading to anomalous points. The triangles clearly mark errors in the data that were effectively confirmed when analysing the data series. Without considering them, the $NOCT_{EXP}$ value is 42.6 ºC while the $NOCT_{MNF}$ is 46 ºC, so the rest of the data is validated.



(a)



(b)

Figure 4. Yearly frequency distributions of weather and operating conditions at the Cádiz-2 PV plant throughout 2010: (a) horizontal and in-plane irradiance, and (b) ambient and cell temperature.

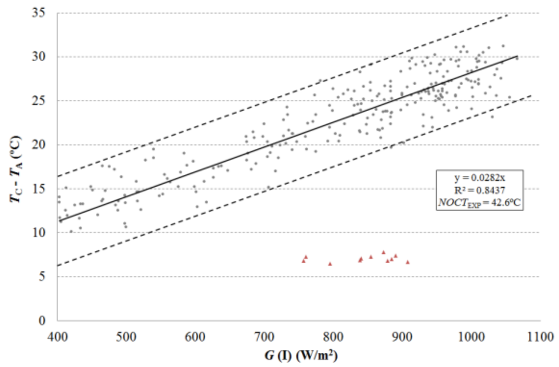


Figure 5. $T_C - T_A$ versus G(I), as recorded every hour at the Cádiz-2 PV plant throughout 2012, once filtered by the *NOCT* measuring conditions. The two dashed lines represent the ±5 ºC margin around the trend (solid line). The outliers clearly mark errors in the data that were effectively confirmed when analysing the data series. Without considering them, the $NOCT_{EXP}$ value is 42.6 ºC while the $NOCT_{MNF}$ is 46 ºC.

2.2 Gain in incident irradiation

In the second case, we plot the daily irradiation gain, $G_D(I)/G_D(0)$, versus the daily horizontal irradiation, $G_D(0)$, and compare the result with those obtained from a simulation of the same location by means of own-made software[1]. Figure 6 shows an example of this exercise for the Cádiz-1 PV plant, a double-axis tracking installation placed at 36.75 ºN. In the figure, the black squares represent the values of the daily irradiation gain obtained from a simulation based on well-established models [22,23]. In particular, for this case we have considered the Erbs model for the K_D/K_T relationship [24] and the Hay model for the distribution of the anisotropic diffuse radiation [25]. In the figure, white diamonds refer to experimentally measured values, with their corresponding regression line. Red triangles mark days with suspiciously low irradiation gains, which therefore do not fulfill the coherence condition. In fact, when looking into the details of these days, in all the cases a tracking problem had occurred in the tracker bearing the reference modules.

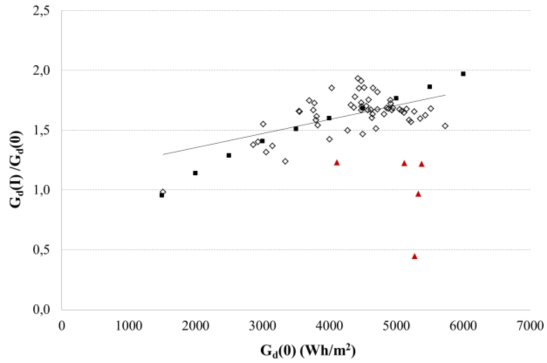


Figure 6. Irradiation gain, $G_D(I)/G_D(0)$, vs horizontal irradiation, $G_D(0)$, in daily values, as recorded in the Cádiz-1 PV plant during October of 2010 and 2011. Black squares represent simulated values while white diamonds and red triangles respectively refer to coherent or incoherent experimental values.

Finally, it must be borne in mind that energy production is taken from the energymeters. This equipment are not only the basis for billing (thus, perfectly reflecting the PV investor interest), but are also of a very good accuracy [18].

3 ENERGY PERFORMANCE

Following a widely extended practice, energy performance is properly characterised by a Reference Yield (the DC energy that a generator would have produced if its efficiency had always been the same as under Standard Test Conditions[2]), a Final Yield (the real AC energy produced) and a performance ratio, *PR* (the ratio between them) [4,14-16,26]. Moreover, we have taken advantage of the PV plant's configuration, with several independent units, to estimate the energy availability (the ratio between the real production and the production in the absence of performance failures), which is a proper index for PV plant reliability [16].

The idea in the back is that two PV arrays at the same location, if free from functioning anomalies, deliver energy at a similar rate. In fact, the absence of anomalies can be identified by the stability in the relative performance during two different periods, as stated in equation (4) for the energy produced:

[1] Available at www.pvcrops.eu

[2] Standard Test Conditions are defined by: G(I)=1000 W/m^2; T_A=25 ºC; and a spectral distribution determined by AM=1.5

$$\left.\frac{E_2}{E_1}\right|_{t_A} = \left.\frac{E_2}{E_1}\right|_{t_B} \qquad (4)$$

where E is the energy produced, t_A and t_B are two different periods and 1 and 2 refer two different PV arrays. A couple of precautions must be taken when applying equation (4):

1) Period t_A should be free from anomalies for both arrays, to set the reference relationship between productions.
2) Array 1 in period t_B must also be free from incidences.

This way, possible failures in array 2 during period t_B will be detected.

In practice, even in periods with no anomalies, there is always a small spread in the energy performance due to varying degrees of dirtiness, shadowing or wind speed effect. Therefore, it is not worth considering the absence of anomalies to the exact correspondence of their relative productions but to a small interval around it. The IES-UPM experience in this sense shows that a deviation of more than 2% in monthly energy productions implies some kind of performance anomaly. It is worth noting that a failure affecting one string of a 100 kW generator (usually made up of around 30 strings) entails a 3% reduction in the production. When considering, for example, a 2 MW plant, this means detecting failures that imply a 0.1% reduction in the total production. This highlights the high level of accuracy of this procedure.

4 RESULTS

Table 1 presents the main characteristics of the PV plants considered and their performance during every analysed period. Averages are divided into three categories depending on the tracking configuration: static, 2-axis with a horizontal primary axis, and 2-axis with a vertical primary axis. The primary axis is the one directly linked to the foundation of the tracker while the secondary is the one that is linked to the primary.

Table I: Annual production results for the 20 PV plants considered in the period 2008-2012. For every installation the following parameters are shown: peak power (MW); analysed year; final and reference yields (kWh/kWp); *PR* and energy availability (%).

Plant	Power	Year	Y_F	Y_R	*PR*	Avail
Alb1	3.2	2008	1757	2132	0.82	96.40
		2009	2080	2322	0.90	99.60
Alb2	2.2	2009	2056	2452	0.84	99.60
		2010	1965	2364	0.83	99.80
Bad	11.3	2009	2016	2724	0.74	99.40
		2010	1893	2458	0.77	99.19
		2011	2021	2556	0.79	99.02
		2012	2108	2547	0.83	99.22
Các	2.1	2009	2142	2528	0.85	99.70
		2010	2194	2675	0.82	99.88
		2011	2054	2487	0.83	99.89
		2012	2204	2839	0.78	99.90
Cád1	3.8	2009	2038	2425	0.84	99.90
		2010	2129	2555	0.83	99.90
		2011	2185	2612	0.84	99.60
		2012	2219	2682	0.83	99.91
Cád2	1.9	2009	2266	2743	0.83	99.96
		2010	2186	2548	0.86	99.89
		2011	2349	2883	0.81	99.89
		2012	2320	2822	0.82	99.96
CRe1	2.0	2009	2161	2629	0.82	99.20
C Re2	2.0	2009	2407	2921	0.82	99.30
		2010	2358	2870	0.82	99.60
Cór	4.5	2009	2012	2456	0.82	99.80
		2010	2067	2523	0.82	99.91
		2011	2264	2726	0.83	99.11
		2012	2168	2718	0.80	99.05
Cue	25.3	2009	1594	1997	0.80	99.78
Gra1	3.0	2009	2050	2639	0.78	96.60
		2010	2036	2586	0.79	99.00
Gra2	1.6	2009	1561	1966	0.79	96.30
		2010	1556	1891	0.82	99.40
Hue	3.3	2009	2389	2758	0.87	99.99
		2010	2190	2558	0.86	99.85
		2011	2312	2733	0.85	99.82
		2012	2375	2742	0.87	99.81
Mur1	2.1	2008	1795	2377	0.76	97.00
		2009	2038	2562	0.80	98.50
Mur2	1.6	2008	2074	2541	0.82	97.70
		2009	2174	2626	0.83	99.00
Sev1	1.5	2009	1975	2645	0.75	98.60
		2010	1962	2518	0.78	99.30
Sev2	3.7	2009	2238	2651	0.84	99.10
		2010	2119	2547	0.83	99.72
		2011	2271	2690	0.84	99.76
		2012	2323	2773	0.84	99.97
Sev3	1.9	2009	1524	2083	0.73	98.90
		2010	1480	1834	0.81	99.43
		2011	1533	1922	0.80	99.76
		2012	1549	1847	0.84	99.54
Tol	3.5	2010	2084	2569	0.81	99.73
		2011	2184	2672	0.82	98.88
Val	9.5	2009	2108	2548	0.83	99.69
		2010	1970	2471	0.80	99.96
		2011	2064	2559	0.81	99.63
		2012	2035	2517	0.81	99.86
Tot	**90.1**	**N.A.**	**2025**	**2496**	**0.81**	**99.43**

Figure 7 shows the frequency distribution of yearly Y_F and *PR* for the different configurations.

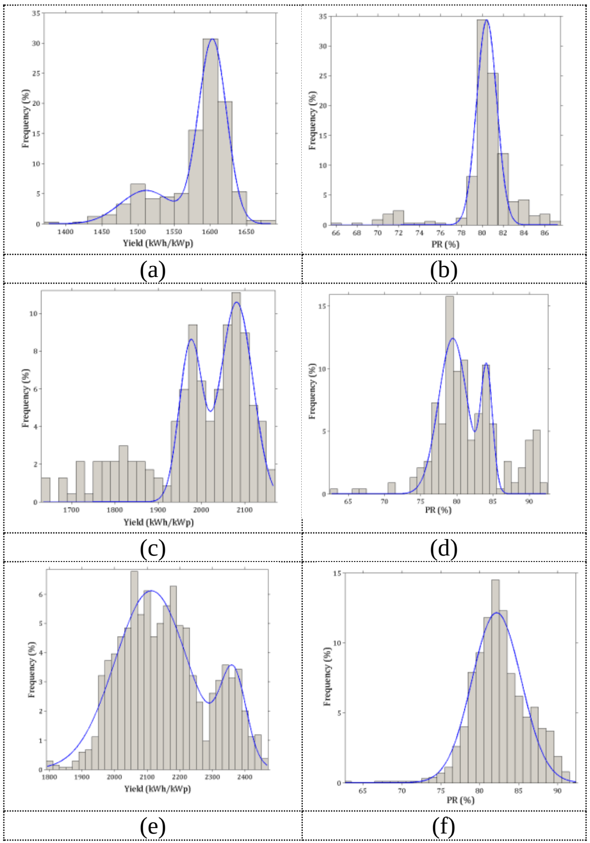


Figure 7. Final yield (kWh/kWp) frequency distribution for (a) static and (b) 2-axis tracking configuration. PR frequency distribution for (c) static and (d) 2-axis tracking configuration.

5 DISCUSSION

The results show that the PV plants produce annually, on average, 1578 kWh/kW with the static configuration, 1972 kWh/kW with a 2-axis configuration with a horizontal primary axis and 2,121 kWh/kW when a 2-axis tracking configuration with a vertical primary axis is considered. The lower production of the 2xhv tracking configuration in comparison with the 2xvh tracking configuration is due to structural limitations of the former trackers [27]. This implies, respectively, average PR values of 0.80, 0.79 and 0.82, which means that the effect of the higher shading losses of the tracking systems are compensated by lower losses due to angle of incidence and low irradiance effects.

PV plants production capacity responds to Gaussian distributions for all the configurations, as can be observed in figure 7. Pictures representing yield behaviour - 7(a), 7(c), 7(e) - show two lobes, as the best fit is achieved through the combination of two Gaussian curves. This double conduct occurs as a consequence of radiation differences between locations and years. Nevertheless, these differences disappear when we move to the *PR* analyses. In the case of the 2xhv tracking, the two lobes appear as a consequence of differences in the tracking systems and, therefore, still exist in the *PR* analysis - 7(d).

Energy availability is 99.0%, 98.4% and 99.6%, respectively, for each tracking configuration considered. It is worth noting that due to the usual incidences in the start-up of the plants, availability tends to be lower (<98%) in the first year. Excluding the initial year, availability rises to 99.5%, 99.3% and 99.8%, respectively.

Typically, the operation and maintenance (O&M) cost in these plants is around €15.000/MW /year. Together with the values of the energy yield, this is equivalent to a maximum of €0.01/kWh.

Currently, the costs of large-scale PV plants have decreased to about €1.1/Wp for static installations and about €1.9/Wp for the 2-axis tracking ones. If we consider the values of the energy yield and O&M costs presented here, a 25-year life-cycle for the PV plant, a 5% discount rate and a financing of 80% of the capital with a 4.5% interest rate for 15 years leads to energy costs of around €0.09/kWh for static plants, €0.12/kWh for 2-axis with horizontal primary axis tracking and €0.11/kWh for 2-axis with a vertical primary axis tracking. All of them are low enough to talk not only about grid parity but also fuel parity in many scenarios.

6 CONCLUSIONS

The performance of several Spanish PV plants, up to a total of 90 MW and 240 MW·year, has been presented. Because of the large size and wide location distribution of this sample, we consider these results representative of the performance of large scale PV plants in Spain. In general, the main conclusions are:

- The final yields are higher than 1,500kWh/kW for static installations, higher than 1,900kWh/kW for the 2-axis tracking configuration with a horizontal primary axis and higher than 2,100 kWh/kW for the 2-axis tracking configuration with a vertical primary axis.

- The annual performance ratio is higher than 0.80, with no significant differences between static and tracking systems.

- Energy availability is higher than 99.5%, with no significant differences between static and tracking systems, at least in the first years of performance. This means that up-to-date trackers have shown a high reliability.

- These results lead to energy costs of about €0.09/kWh for static installations and about €0.11/kWh for 2-axis tracking systems, which are low enough to talk not only about grid parity but also fuel parity in many scenarios.

ACKNOWLEDGEMENTS

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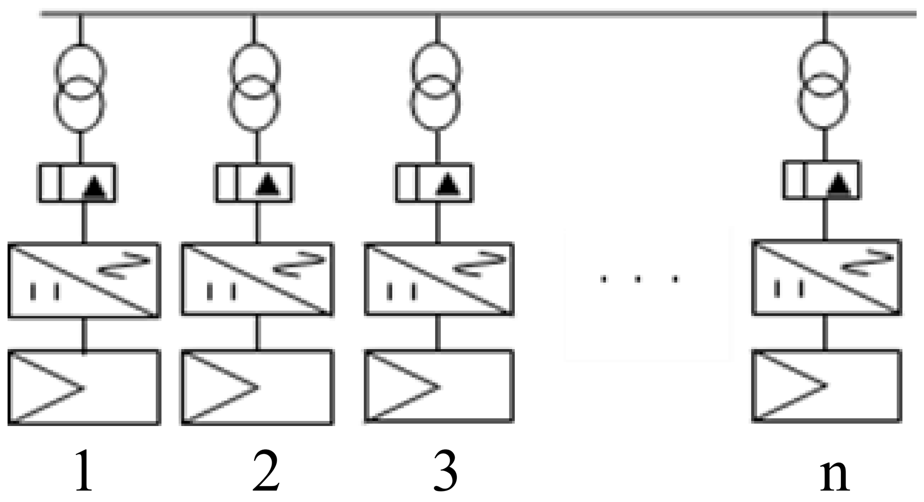
EXPERIMENTAL DATABASE

$G(0)$, T_A, S_W from meteorological stations

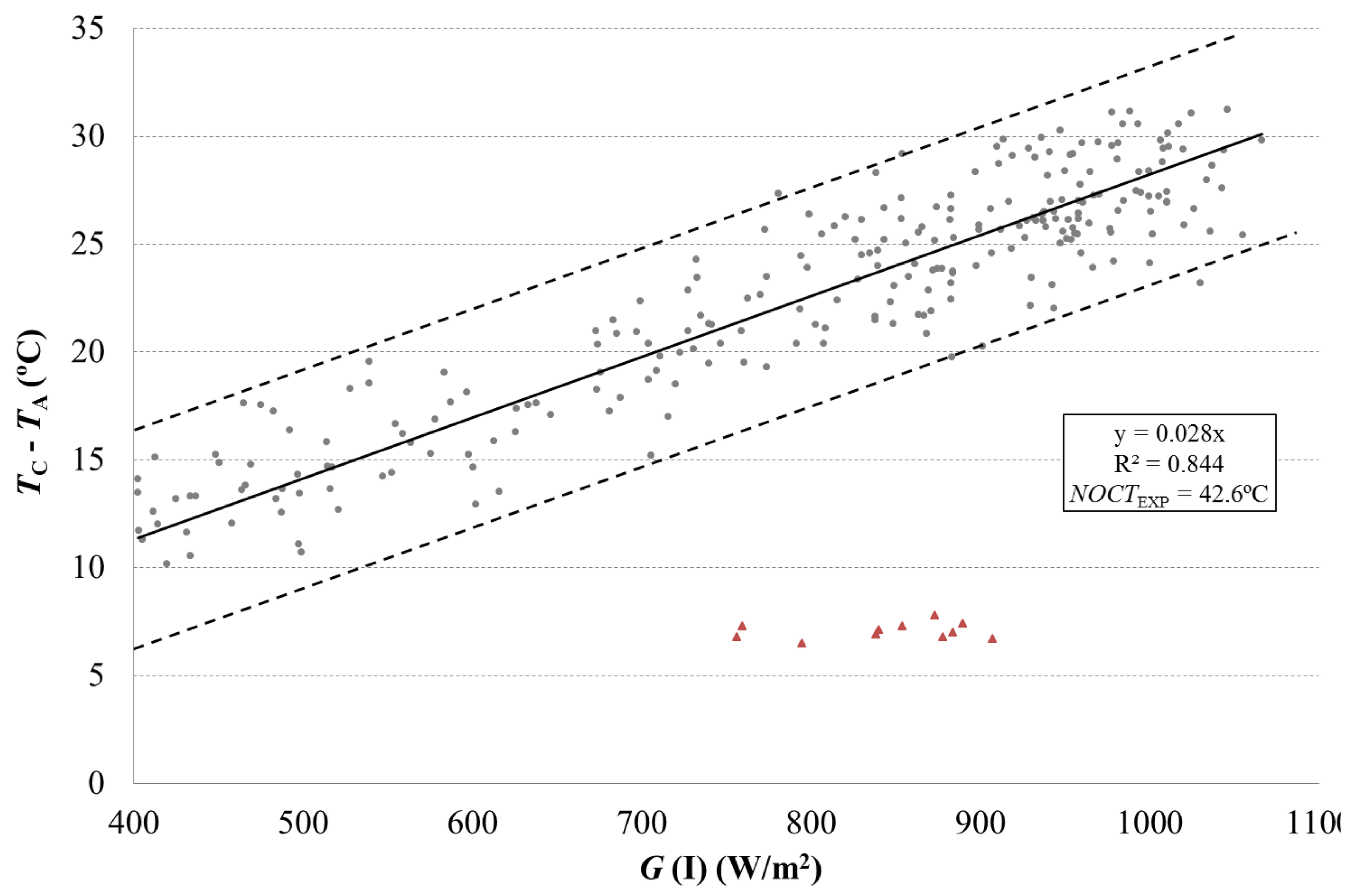
$G_{ef}(I)$, T_C from reference modules

19 PV plants // Same configuration: 100 kW units

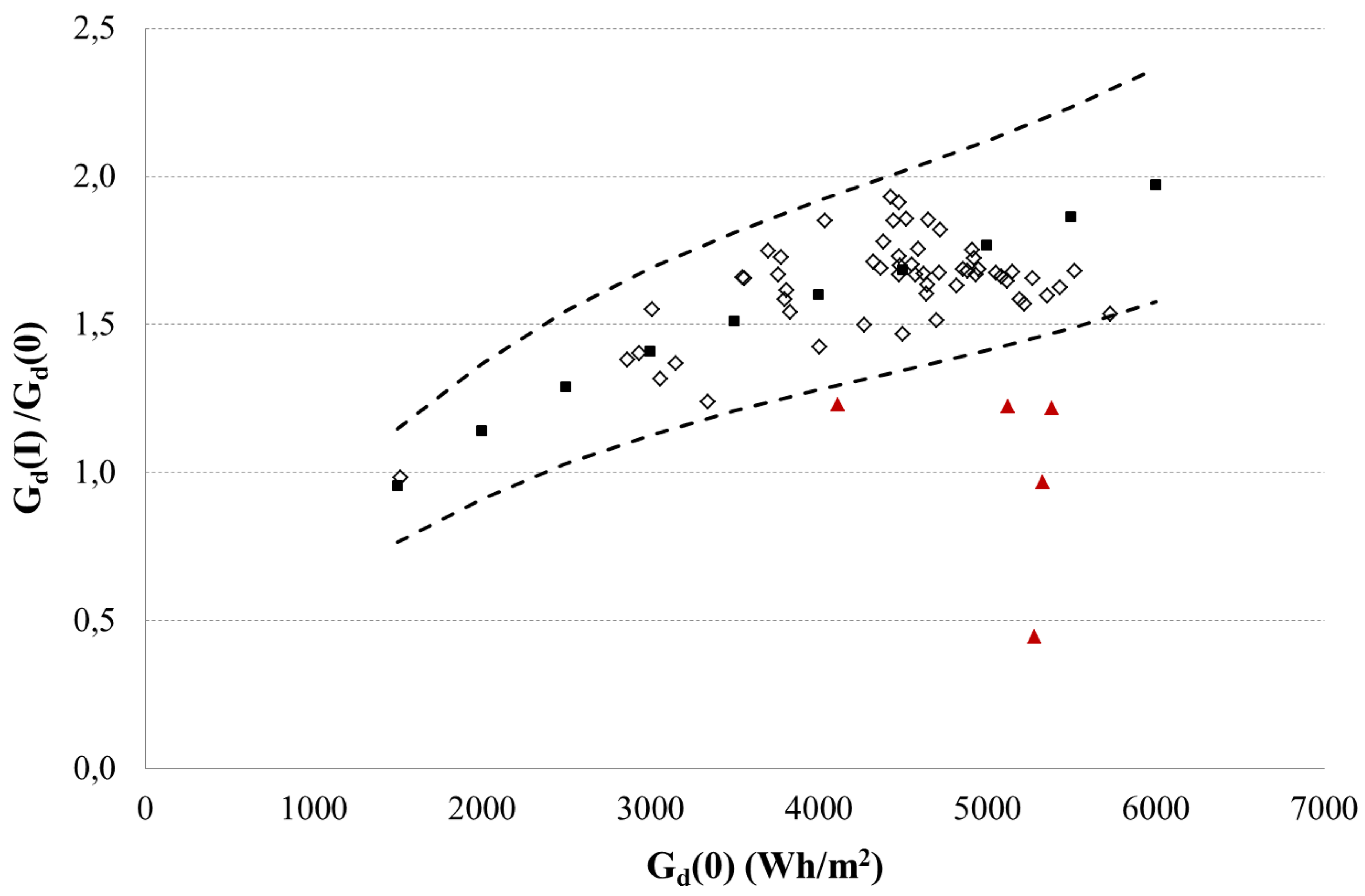
90.1 MW // 1-2 years of operation // 240 MW·year



DATA CONSISTENCY



Experimental NOCT

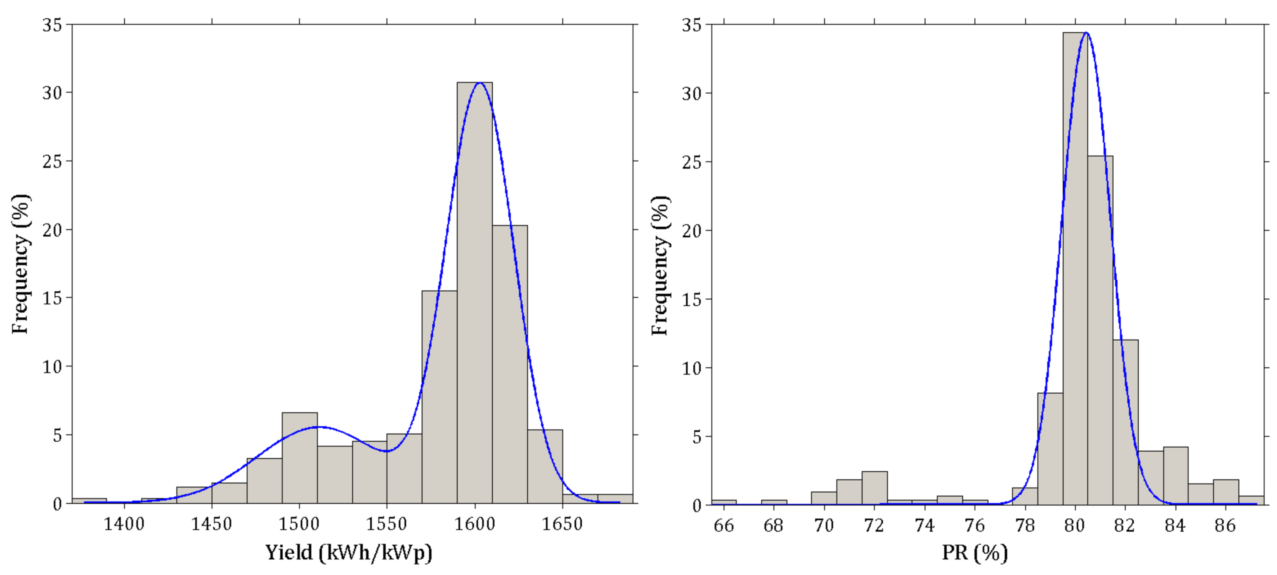


Irradiation gain

$$\left.\frac{E_2}{E_1}\right|_{t_A} = \left.\frac{E_2}{E_1}\right|_{t_B}$$

Energy availability

PERFORMANCE RESULTS

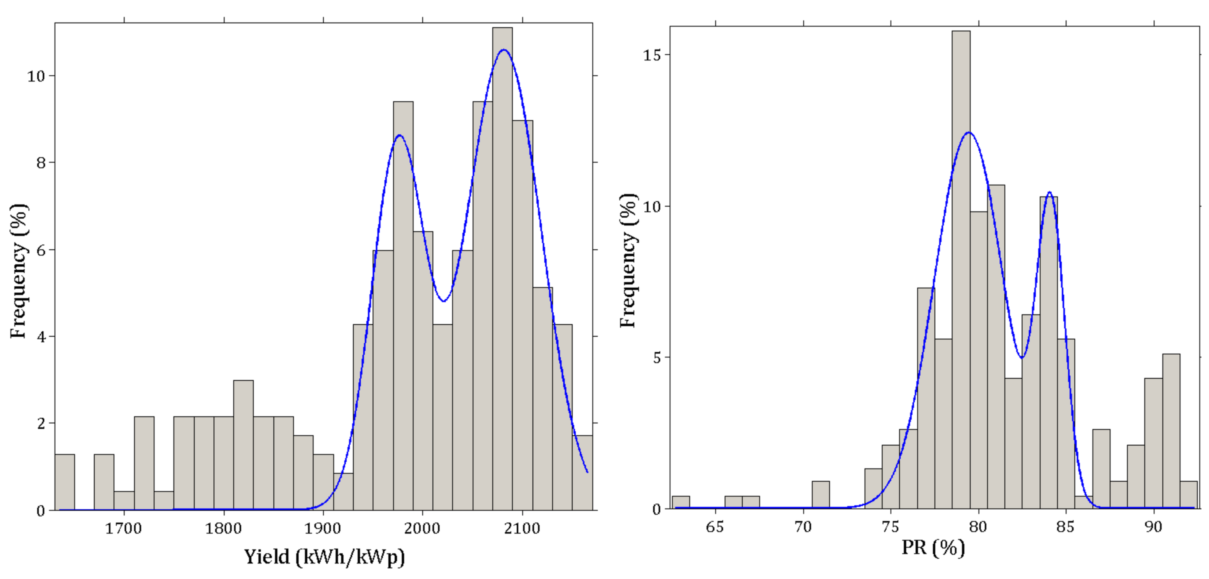


<u>Static structures</u>

Yield = 1,578 kWh/kWp

PR = 0,80

Availability = 99,0%

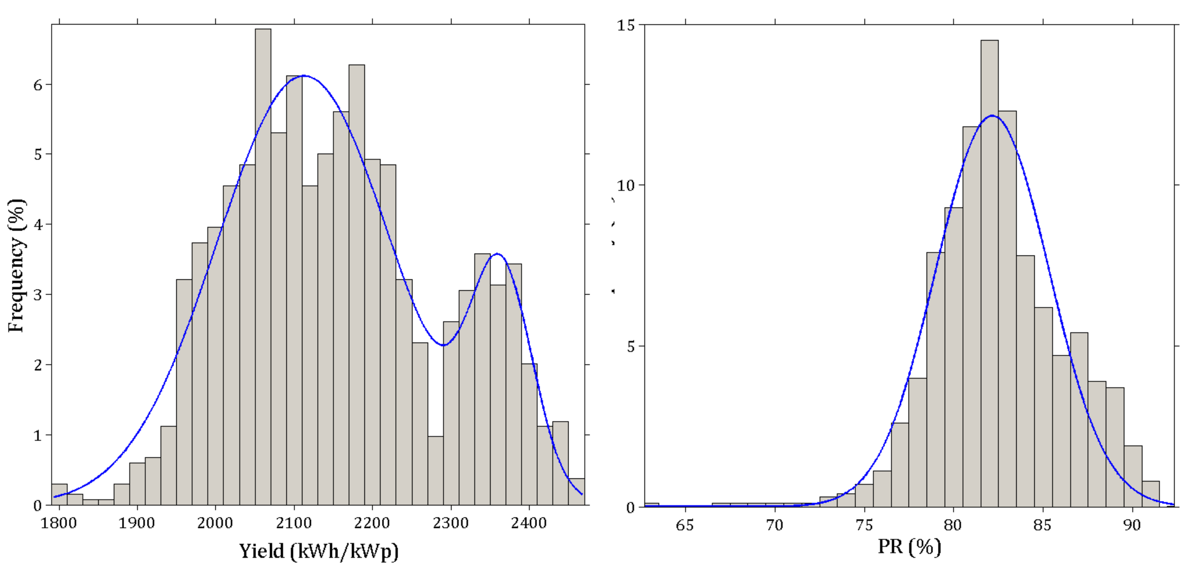


<u>2x- tracking horizontal primary axis</u>

Yield = 1,972 kWh/kWp

PR = 0,79

Availability = 98,4%



<u>2x- tracking vertical primary axis</u>

Yield = 2,121 kWh/kWp

PR = 0,82

Availability = 99,6%

CONCLUSIONS

- Final yield over 1,500 kWh/kWp in static systems and over 2,100 in two-axis systems
- No appreciable differences in *PR* values between different tracking configurations: larger shading losses compensated by lower losses due to angle of incidence and low irradiance effects. *PR* is usually over 0.80.
- No appreciable differences in energy availability between different tracking configurations. Excluding the first year of operation (affected by start-up problems), it stands between 99.3% and 99.8%.
- No appreciable power degradation in the first 4 years of operation.
- These results lead to energy costs of about €0.09/kWh for static installations and about €0.11/kWh for 2-axis tracking systems.