Characterization in power and energy of two photovoltaic grid connected systems of different technologies (crystal silicon and thin film), operating in Lima

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Abstract. The Centre for Renewable Energies of the National University of Engineering of Peru (CER-UNI) and the Research and Development Group in Solar Energy (IDEA Group) of the University of Jaén - Spain have elaborated the present work that is based on the installation, instrumentation and monitoring of two Grid Connected Photovoltaic Systems at UNI, one with crystalline PV modules and the other with second generation PV modules of thin film, with amorphous microcrystalline tandem technology. An energy characterization of both systems has been made according to IEC 61724-1: 2017 norm, using two procedures: First, plotting the I-V curves of both PV generators and transferring the measured maximum power data to Standard Conditions, SC, using the methods of Evans Osterwald and Constant Form Factors. Then, the Power at SC of the PV generators and the complete systems was obtained under the protocols of the Solar Energy Institute of the Polytechnic University of Madrid, and validated by the IDEA group of the University of Jaén. Finally, the results obtained were analysed and the most relevant conclusions of the work are reported.

1. Introduction

The project “Emerging with the sun” is developed in collaboration between the University of Jaén, Spain, and the Renewable Energy Center of the National University of Engineering, (CER UNI), Lima, and till now has achieved the following general results:

a) Implementation at the CER-UNI of a laboratory of experimental instrumentation and photovoltaic systems connected to the grid for testing and training, with which the performance of a PV panel of up to 1.5 kWp can be studied and its quality determined [1].

b) Implementation of four Grid Connected Photovoltaic Systems, GCPS, with remote monitoring, instrumentation for research and teaching, two at the UNI, one at the National University of San Agustín in Arequipa (UNSA) and one at the National University Jorge Basadre Gromann in Tacna (UNJBG), as well as a point to charge cell phones and laptops at the UNI campus with the technical configuration of an GCPS [2]. The main technical characteristics of these facilities are given next:

SFCR3K-UNI, LIMA: PV panel of 15 modules SW215, totaling 3225 WP, an inverter Steca-Grid 3000, of 3kW.

SFCR3K-UNSA, AREQUIPA y FVCR3K-UNJBG, TACNA: PV panel of 12 modules SW275, totaling 3300 WP, an inverter Steca-Grid 3010x, of 3kW.
SFCR3K-LABSOLCER: PV panel of 27 modules SHARP NA-F128GK of 128W each, double thin layer of $\alpha$Si/$\mu$Si, with 3 parallel strings of 9 modules each in series, an inverter SMA, SUNNYBOY of 3.0 kW [3] [4].

ECOCHARGER SOLAR – UNIFIM: to charge mobile phones and laptops, including 4 PV modules ISOFOTON I-106/12, of 106W each, and an microinverter AP systems YC500A of 500W. These four GCPS are monitored from the LABSOLCER individually and in conjunction with the installed instrumentation and software that allows the energy characterization of the GCPS according to the IEC 61724-1:2017 standard on the basis of information measured with sensors and instruments that follow the daily behavior of the irradiance, ambient temperature, module temperature and parameters of the PV generator, the DC/AC inverter and the DC and AC electric power quantities involved [5].

The systematic operation of the 5 mentioned PV installations, plus the Solar Energy Laboratory of the CER-UNI, which has been called LABSOLCER, will allow the study of potentially expectant technological variants for some national climates, such as the case of thin-film PV modules, real results that can only be achieved through the development of systematic and prolonged experimental processes that allow the capture and accumulation of reliable information corresponding to parameters and variables of greater incidence in their behavior, specific to the technology and local environment.

2. Description of the system
The SFCR3K-UNI was installed on a pergola of approximately 2.5 meters high and has been operating since December 2013. The installation of the monitoring system was done in April 2015 and there are operating data of the system under real conditions of operation since May of that year.

The SFCR3K-LABSOLCER, also named SFCR-THIN FILM, was configured and installed with 2nd generation thin film modules, manufactured by Sharp with amorphous microcrystalline tandem technology. The main reason for installing this type of technology, currently marginal in the PV market, has clearly research-oriented objectives, since it is in the interest of the worldwide scientific community working in the sector to evaluate the spectral behavior of these technologies in places near to the equator subjected to climates as particular as is the case in Lima.

These two SFCRs are about 1 km apart within the UNI campus, the first near the Faculty of Sciences and the second at the LABSOLCER, near the Faculty of Mechanical Engineering and are shown in the images of figure 1 below.

![Image of SFCR3K-UNI and SFCR3K-THIN FILM](image.png)

Figure 1. On the left the SFCR3K-UNI and on the right (below) the SFCR3K-THIN FILM and (above) you can see the two FV cells used as sensors of irradiance.
In the images of figure 1 we can see the accumulated dust on the surface of the SFCR3K-UNI panel that is difficult to clean, and on the first string of the SFCR-THIN FILM with 4 months without cleaning, in the process of being studied.

3. Methology
As a basic option, we have proceeded to draw IV curves of both PV generators and [6], subsequently, we have made the extrapolation to Standard Measurement Conditions (CEM) of the maximum power data obtained using the methods proposed by Evans and Osterwald and Constant Form Factor that are described briefly below.

EVANS: A simplified procedure is presented [7] to predict the average long-term monthly electricity production of photovoltaic arrays. It is restricted to arrangements with passive cooling and tracking of the maximum power point, but is applicable to both flat fixed arrays facing north as well as with 2-D tracking. The procedure combines basic parameters that characterize the arrangement with the local monthly average temperature and the monthly $K_T$ (ratio of the total radiation in the horizontal plane to the extraterrestrial radiation) to produce an average monthly efficiency that, when multiplied by the monthly irradiance on the modules gives the energy produced, with the following definitions:

$$Q_{ae} = \frac{\eta \cdot A \cdot \Sigma I_i}{N_d}$$

(1)

The monthly average efficiency is:

$$\eta = \eta_r \cdot [1 - \beta \cdot (T_c - T_a) - \beta \cdot (T_a - T_M) - \beta \cdot (T_M - T_r) + \gamma \cdot \log_{10} I]$$

(2)

with:

- $Q_{ae}$: Average monthly energy of the photovoltaic panel
- $\eta$: Monthly average efficiency of the panel
- $A$: Area of the panel
- $I_i$: Hourly solar energy incident on the panel
- $N_d$: Number of days per month
- $\eta_r$: Efficiency at CEM
- $\beta$: Temperature coefficient of the photovoltaic module
- $T_c$: Average monthly module temperature
- $T_a$: Ambient temperature
- $T_M$: Average monthly ambient temperature
- $T_r$: Reference temperature for the efficiency of the arrangement
- $\gamma$: Coefficient of intensity for the efficiency of the arrangement

**Method proposed by Osterwald** [8-9]:
The method converts the operating measurements of the photovoltaic system to standard conditions of measurement (CEM), where the specifications can be categorized into three areas: temperature of the array, the total incident irradiance level and the distribution spectrum of the incident irradiance. The method tries to know how the system responds to different conditions, measuring the differences, and then correcting or converting the measured values to CEM.

For the temperature, the operating parameters ($V_{oc}$, $I_{sc}$, FF) have a linear behavior with the variation of the temperature, which can be represented by the following formula where $P$ is an operating parameter.

$$P_{25} = P_T + \frac{dP}{dT} (25 - T_x)$$

(3)
where \( T_x \) is the temperature (°C) at which the parameter \( P_{T_x} \) is measured and \( P_{25} \) is the value at 25 °C.

The temperature coefficients are obtained from the technical information of the manufacturers of the modules.

For the total irradiance, in most cases, it is reasonable to assume that \( I_{cc} \) has a linear behavior with respect to the irradiance where the intersection is very close to zero. Consequently, the following relationship is obtained:

\[
I_{cc}^0 = I_{cc}^x \frac{1000 \text{ Wm}^{-2}}{E_{tot}}
\]  

(4)

where super indexes 0 and x refer to standard and non-standard conditions of measurement, respectively.

For the measured spectrum, when a calibrated reference cell is used to measure a system of unknown technology by the reference cell method, 2 errors appear, one in the measurement of \( I_{cc} \) due to the difference of spectral distribution, and another one between the radiation source and the desired reference spectrum. The magnitude of this error can be determined using the spectral mismatch parameter \( M \). For the definition of \( M \), one determines:

\[
I_{cc}^{Cel} = \int_a^b E_{Irr} (\lambda). RS^{Cel} (\lambda). d\lambda
\]

(5)

where \( I \) is the current per area, \( Cel \) is the reference cell or the cell of unknown technology, \( Irr \): refers to the irradiance of the simulator or reference. Then \( M \) has the following expression:

\[
M = \frac{I_{Descon}^{Cel}}{I_{Simul}^{Descon}} \cdot \frac{I_{Cel \ Refer}}{I_{Simul}^{Cel \ Refer}}
\]

(6)

where: \( Descon \) is the cell of unknown technology; \( Cel \ Refer \) is the Reference cell; \( Simul \): Irradiance of simulator; and \( Refer \): reference irradiance.

In the case of the SFCR-CIENCIAS, the experiment was performed with the presence and absence of dust in the irradiance sensor used for monitoring. This has allowed us to make an approximate estimate of the losses directly related to the dirt accumulation presented on the PV generator. This experimental campaign was carried out using a PV Module Performance Tester brand EKO, model MP11 that offers a measurement range of the I-V curve between 1000 V/30A with a maximum of 18 kW. As a more advanced option, we have proceeded to obtain the power at CEM of the PV generators and the complete system using the protocols and procedures proposed by the group of systems of the Solar Energy Institute of the Polytechnic University of Madrid and validated by the Research and Development Group in Solar Energy of the University of Jaen. For this, clear days have been chosen, with high levels of irradiance [10-11].

The SFCR - FC is monitored with an instrument set of CARLO GAVAZZ, called Eos-Array, and is a compact, simple, versatile modular solution for the management and control of photovoltaic plants, which, in this case, consists of: VMU-M master unit and data logger; VMU-S string controller; VMU-P unit of environmental variables, plus an energy analyzer module. The irradiance sensor is a 15x20 cm PV cell properly calibrated and located as shown in Figure 1, the module temperature sensor is a PT100 adhered at the back of one of the modules and the temperature sensor of the environment is also a PT100. The sampling of the monitoring consists of recording of values every 15 seconds during the 24 hours of the day. The registers started April 2015 to the present. Each monitoring system registers the following parameters: AC voltage, AC current, active power, apparent power, reactive power, frequency, power factor, total energy, partial energy, DC voltage, DC current, DC power, irradiance, module temperature and ambient temperature.
4. Results
In what follows we present results corresponding to the THIN FILM SFCR referring to the continuous electrical energy \((\text{Edc in kWh / day})\) produced by the PV generator and the alternating electrical energy \((\text{Eac in kWh / day})\) transformed by the inverter.

Table 1. Average daily operating results with the SMA monitoring system.

|       | Jan   | Feb   | Mar   | Apr   | May   | Jun   | Jul   | Aug   | Sep   | Oct   | Nov   | Dec   |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \(H(\text{kWh/m}^2\text{day})\) | 5.27  | 5.22  | 6.00  | 5.44  | 3.29  | 2.31  | 1.67  | 1.89  | 2.82  | 3.58  | 5.60  | 5.47  |
| \(\text{Edc (kWh/day)}\)      | 16.92 | 16.77 | 19.63 | 17.91 | 10.72 | 7.55  | 5.51  | 6.19  | 9.17  | 11.75 | 17.39 | 18.21 |
| \(\text{Eac (kWh/day)}\)      | 15.94 | 15.86 | 18.60 | 16.95 | 10.02 | 7.01  | 5.01  | 5.67  | 8.56  | 11.05 | 16.65 | 17.20 |

Table 2. Average daily operating results with the own monitoring system.

|       | Jan   | Feb   | Mar   | Apr   | May   | Jun   | Jul   | Aug   | Sep   | Oct   | Nov   | Dec   |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \(H(\text{kWh/day})\)      | 4.48  | 5.63  | 5.74  | 5.02  | 3.00  | 1.88  | 1.98  | 1.69  | 2.52  | 3.73  | 5.22  | 4.78  |
| \(\text{Edc (kWh/day)}\)    | 15.22 | 18.08 | 18.53 | 16.26 | 9.18  | 6.18  | 6.35  | 5.65  | 8.15  | 11.76 | 17.10 | 17.18 |
| \(\text{Eac (kWh/day)}\)    | 15.19 | 18.03 | 18.51 | 16.22 | 9.18  | 6.18  | 6.32  | 5.59  | 8.08  | 11.70 | 16.96 | 17.09 |

In compliance with IEC61724, productivities, losses, efficiencies and PR are given in table 4.

A. Performance
The yields are the ratios of an amount of energy and the nominal power of the arrangement \(P_0\). These indicate the actual operation of the array in relation to its nominal capacity. Yields have units of kWh/kW, the ratio is equivalent to hours, whereby the yield indicates the amount of time the array would require to be operated at \(P_0\) to provide the amount of energy measured during the reported period [12], [13].

The “energy efficiency of the PV array (\(Y_A\))” is the ratio between the DC output power and the nominal kW of the PV array installed in Standard Measurement Conditions (CEM).
The “final system performance (\(Y_f\))” is the ratio between the AC output power and the rated kW of the installed PV array.
The “reference performance (\(Y_r\))” is calculated by dividing the total irradiance through the irradiance of the reference plane of the module.
The reference yield represents the number of hours during which the solar radiation would have to be equivalent to the reference irradiation level to contribute the same incident solar energy. If the reporting period is equal to one day, the \(Y_r\) would be, in effect, the equivalent number of sunshine hours in the reference irradiance per day.

B. Overall performance PR
The overall yield is the quotient of the \(Y_f\) system performance with the reference \(Y_r\) yield, and indicates the overall effect of losses on the system output due to both the temperature of the array and the inefficiencies or failures of the system components. The calculation of the referred returns and the PR is presented in the following table.

\[
\frac{Y_A}{P_0} = \frac{E_A}{P_0} \quad Y_f = \frac{E_{out}}{P_0} \quad \frac{H_r}{G_{ref}} \quad \frac{Y_r}{Y_f} \quad PR = \frac{E_{out}/P_0}{(H_r/G_{ref})}
\]

C. Performance
To corroborate the good functioning of the system, it has been characterized in power by applying Eduardo’s method, processing the data of 5 days of good irradiance: 15, 16, 18, 19, 28 of February 2017 and the results are presented in the following figures.
Figure 2. Characteristic power of the SFCR3K-THIN FILM. 3.305 kW, is obtained and the curve is cut because the power of the inverter is 3 kW.

Figure 3. Correlation between direct (DC) and alternating power (AC).

Figure 4. I-V curve (a) and power curve (b) for the THIN FILM SFCR in real measurement conditions for November 24, 2016, taken at the LABSOLCER.

In general, the results of the Thin Film system are within a normal range of operation.

Results of SFCR3K-UNI

Table 3. Irradiance H (kWh / m\(^2\)day), continuous electrical energy Edc (kWh / day) and alternating electric power (kWh / day) after 2 years of monitoring.

|       | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| H(kWh/m\(^2\)day) | 3.88 | 4.86 | 4.86 | 4.24 | 2.85 | 1.72 | 1.75 | 1.54 | 2.12 | 2.72 | 2.73 | 3.07 |
| Edc (kWh/day)    | 8.49 | 12.09 | 11.84 | 10.57 | 7.43 | 4.46 | 4.41 | 3.35 | 4.94 | 6.86 | 5.14 | 4.72 |
| Eac (kWh/day)    | 8.36 | 11.90 | 11.66 | 10.41 | 7.32 | 4.38 | 4.32 | 3.27 | 4.84 | 6.75 | 5.07 | 4.66 |
The above results are with the dirty system and sensor. This means that we can have information that leads to error. Although it is clear that something is not working well because the $Y_f$ is too low. We have two ways of acting: a) observing Curve IV (Figure 5) where it is seen that the Silicon system has a serious operating problem due to dirt, and b) processing the SFCR FC data using as a sensor of irradiance (H) the sensor located in the installation of Thin Film, that is, processing those data with those of the THIN FILM sensor. If we repeat the calculations of IEC 61724, the results are very different and somewhat more coherent (Figure 6, Table 4).

**Table 4.** Synthesis of the results of applying the IEC61724 standard to both instrumental systems measured values of irradiance, continuous and alternating electric power, performance indicators and efficiencies calculated with irradiance data with dirty sensor and clean sensor. Note the substantive differences for irradiance, efficiencies and PR (annual). An erroneous reading of irradiance can generate misleading performance values.

|                     | Own monitor | SMA monitor | Difference | Sensor G dirty, System Si | Sensor G clean, System Si | Difference |
|---------------------|-------------|-------------|------------|---------------------------|---------------------------|------------|
| $H$ (kWh/m²/year)   | 1389        | 1477.21     | 5.95%      | 1105                      | 1389                      | 20.45%     |
| $E_{dc}$ (kWh/year) | 4787        | 4793.27     | 0.13%      | 2552                      | 2552                      | 0.00%      |
| $E_{ac}$ (kWh/ano)  | 4541        | 4507.04     | -0.75%     | 2511                      | 2511                      | 0.00%      |
| $Y_r$ (kWh/kWp year)| 1389        | 1477.21     | 5.95%      | 1105                      | 1389                      | 20.45%     |
| $Y_a$ (kWh/kWp year)| 1313        | 1386.94     | 5.34%      | 791                       | 791                       | 0.00%      |
| $Y_f$ (kWh/kWp year)| 1245        | 1304.12     | 4.50%      | 779                       | 779                       | 0.00%      |
| $L_c$ (kWh/kWp year)| 72          | 87.25       | 17.12%     | 310                       | 594                       | 47.81%     |
| $L_{bos}$ (kWh/kWp year) | 68      | 82.91       | 18.39%     | 13                        | 13                        | 0.00%      |
| Efficiency of PV generator | 9.1% | 8.5% | -6.28% | 9.2% | 7.3% | -26.03% |
| Efficiency of BOS    | 94.9%       | 94.0%       | -0.88%     | 98.4%                     | 98.4%                     | 0.00%      |
| Efficiency of system  | 8.6%        | 8.0%        | -7.22%     | 9.1%                      | 7.2%                      | -26.39%    |
| PR (annual)           | 89.9%       | 88.5%       | -1.63%     | 70.8%                     | 56.3%                     | -25.75%    |

**Figure 5.** I-V curve (a) and power curve (b) for the SFCR FC, the shape obtained for the curve I-V reveals serious problems of operation due to dirt and, eventually, others to be discovered.
The results with a clean sensor (the one located in the SFCR THIN FILM) show a noticeable decrease of the PR, which translates into a very striking increase of the losses: the losses by dust are 30.6% in June and 53% in December.

![Figure 6](image)

**Figure 6.** Relationship between the losses of the rest of the system (Lbos), loss of capture (Lc) and system performance (Yf) by measuring the irradiance with the sensor cell with and without dirt of dust.

Nether the less, we proceed to characterize the system energetically by applying formulas that give us some indication of the state of its operation if it were totally clean, applying Eduardo’s Method for days 15, 16, 18, 19, 28 of February 2017.

![Figure 7](image)

**Figure 7.** A system power of 2931 W is obtained in STC (using the sensor dirt of dust, which has a mean capture loss of 32%) and a system power of 2206 W in STC.

These data differ much from what the manufacturer says, that is we have a case in which a PV system does not work properly, regardless of the associated dirt problems.

5. Conclusions

There is a problem of dirt and serious contamination that seriously affects the functioning of the system. After doing a quality control of the Silicon installation, and once the dust losses have been eliminated, the preliminary conclusion is that the system does not work according to the original design parameters. This means that the PV modules do not correspond to the manufacturer’s power rating or that they have degraded at a higher speed than expected.
6. References

[1] Espinoza R, Luque C and De la Casa J 2015 Comparación de indicadores de rendimiento sobre sistemas fotovoltaicos conectados a la red – Proyecto emergiendo con el Sol, XXII Simposio Peruano de Energía Solar, Arequipa-Perú

[2] Espinoza R, Luque C, Muñoz E, De la Casa J and Aguilera J 2016 Emerging with the SUN: International technical and training support project, Proc., Engineering and Environment Knowledge Week, Paris-France

[3] IEC 61724-1 2017, Photovoltaic System Performance, Part 1: Monitoring

[4] Espinoza R, Luque C, Muñoz E, de la Casa J and Aguilera J 2016 Missing Gaps in the Challenge of Massive Intervention of Grid-Connected PV Systems in Peru. Proc., 32nd European Photovoltaic Solar Energy Conference and Exhibition, pp.3048–3052

[5] Ramos E, Espinoza R y de la Casa J 2017 Comparación técnica económica de sistemas fotovoltaicos conectados a la red en las ciudades de Lima, Arequipa y Tacna. Proc. Conf., XXII Congreso Nacional de Ingeniería Mecánica, Eléctrica y Ramas Afines, Lima-Perú

[6] Duran E, Piliougine M, Sidrach M, Galan J y Andañar J 2008 Different methods to obtain the I-V curve of PV modules: Conf., Record of the IEEE Photovoltaic Specialists

[7] Evans D 1981 Simplified method for predicting photovoltaic array output, Proc. Energy Solar Vol 27 pp 555-560

[8] Osterwald C 1986 Translation of device performance measurements to reference conditions, ed Sol chapter 18 pp 3-4 pp 269-279

[9] Muñoz E, Nofuentes G, Fuentes M, De la Casa J and Aguilera J. 2016, DC energy yield prediction in large monocrystalline and polycrystalline PV plants: Time-domain integration of Osterwald's model, Proc. Energy, vol 114, pp 951-960

[10] Montes R J, Torres R M, De La Casa J, Firman A., Cáceres M. (2016) Software tool for the extrapolation to Standard Test Conditions (STC) from experimental curves of photovoltaic modules. Proc. Technologies Applied to Electronics Teaching, TAAE 2016

[11] Muñoz J, Martinez M F and Lorenzo E 2011, On-site characterization and energy efficiency of grid-connected PV inverters. Proc. Photovolt. Res. Appl.19 pp 192–201

[12] Nofuentes G, Aguilera J, Santiago R L, De la Casa J and Hontoria L 2006, A reference-module-based procedure for outdoor estimation of crystalline silicon PV module peak power. Proc. Photovolt: Res. Appl., 14 pp 77–87

[13] Martinez M F, Lorenzo E, Muñoz J and Moretón R 2012, On the testing of large PV arrays. Proc. Photovolt: Res. Appl., 20 pp 100–105