COMPARISON OF PYRANOMETER AND SI-REFERENCE CELL SOLAR IRRADIATION DATA IN LONG TERM PV PLANT MONITORING

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ABSTRACT: At the highest grid connected PV plant in Europe, the 1.1 kW_p installation at the Jungfraujoch (elevation 3454 m), the in-plane solar irradiance at the vertically (facade) mounted arrays has been measured both by a pyranometer and by a calibrated (Si) reference cell as part of an extended PV system performance study of nearly 2 years duration. On the basis of these results we shall discuss the impact of the radiation sensor characteristics on the performance data.

1. INTRODUCTION

The pyranometer (thermo-pile type) is the standard device for solar radiation measurements in meteorology; since it integrates the global solar radiation input over the whole spectrum and also, mounted horizontally, over the effective part of the solid angle. Unfortunately, the pyranometer is not a device of rugged construction; it has to be handled with care. Its price is high; periodic (yearly) recalibrations have to be done; the low intensity signal output must be properly amplified and shielded from noise. Thus, there has been a strong motivation to use calibrated Si-cells instead of pyranometers.

In the past there have been numerous studies comparing irradiance data from pyranometers with those from calibrated Si-cells at different spectral conditions, angles of incidence etc. However, the basic fact that a Si-device does not respond to the infrared part of the spectrum casts doubts on the reliability of Si-based irradiance data for the study of the energy balance of the atmosphere.

On the other hand, PV system monitoring is concerned mainly with the optimal use of the installation: how close does the real system approach the limits of an ideal (reference) installation? It may be assumed that the reference installation has a spectral and spatial response similar to that of a calibrated Si-cell.

Here we present some results of long-term monitoring from a PV installation having both a pyranometer and a Si-cell as radiation sensors. In particular, the following questions are discussed:

- What procedures are necessary to provide reliable working conditions for pyranometers in a harsh environment.
- How much are the average differences in the radiation data of both devices in the monthly and yearly sum.
- What additional uncertainty (scatter) is introduced in the array performance data when referred to irradiance measurements with pyranometers

2. MONITORING PROCEDURE

The highest European PV plant, the 1.13 kW_p grid-connected installation at the Jungfraujoch (elevation 3454 m) was monitored since November 1993. Together with the electrical data of the plant the in-plane solar irradiance at the vertically (facade) mounted arrays was measured both by a pyranometer (Kipp & Zonen CM21) and by a calibrated (Si) reference cell (Siemens M1R). All data recorded are hourly averages of a large number of scans.

Between December 1993 and June 1994, the dome of the pyranometer was not heated, due to a failure of the power supply of the heating. Thus on some days ice for-mation or snow deposition caused the pyranometer to read lower irradiance values than the Si-sensor. After replacement of the power supply by a properly designed device in July 1994, the pyranometer dome was heated again. Since then the pyranometer readings usually were higher than those of the reference cell (due to the contribution of the low frequency part of the spectrum).

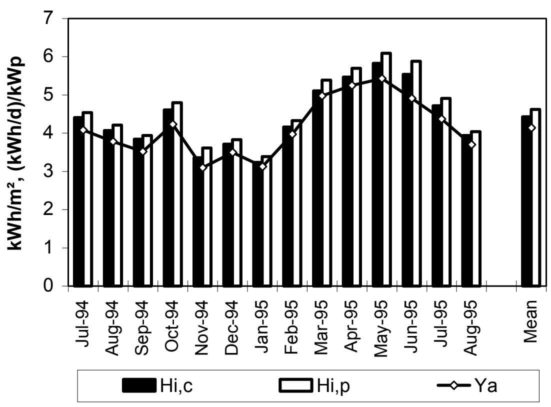
3. MONTHLY MEAN VALUES

On days with medium to high irradiation, pyranometer readings were up to a few percent higher than reference cell readings, whereas on days with low irradiation reference cell readings were usually higher. In the monthly mean this difference usually remains in the range of 2-6%, except for months with heavy snow falls (e.g.Nov.94: 7.4%). The following Table 1 and Fig. 1 show these data together with the corresponding array yield Y_a, which is the mean daily energy output from the array, divided by its nominal power (P_o = 1.13 kW_p)

Table 1: Comparison of mean daily irradiation [(kWh/m^2)/d] at Jungfraujoch (3454m)
- Hi,c measured with a calibrated cell,
- Hi,p measured with a pyranometer

Month	Hi,c	Hi,p	Ya	Hi,p/Hi,c
Jul-94	4.41	4.54	4.08	1.029
Aug-94	4.07	4.21	3.78	1.034
Sep-94	3.84	3.94	3.52	1.026
Oct-94	4.61	4.80	4.23	1.041
Nov-94	3.36	3.61	3.10	1.074
Dec-94	3.71	3.83	3.50	1.032
Jan-95	3.24	3.39	3.13	1.046
Feb-95	4.16	4.33	3.97	1.041
Mar-95	5.11	5.39	4.98	1.055
Apr-95	5.47	5.70	5.25	1.042
May-95	5.83	6.09	5.43	1.045
Jun-95	5.54	5.88	4.91	1.061
Jul-95	4.72	4.91	4.37	1.040
Aug-95	3.94	4.04	3.70	1.025
Mean	4.43	4.62	4.14	1.043

Fig.1: Monthly Irradiances and Array Yields

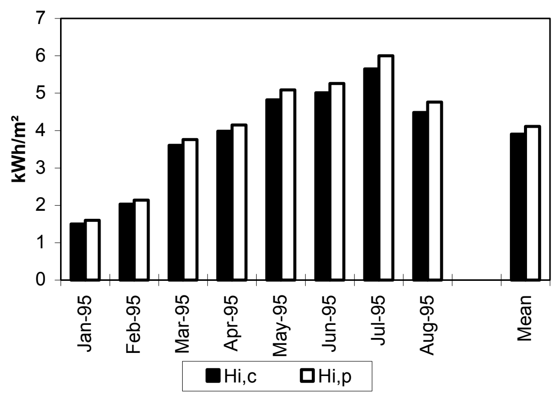


At ISB's test centre for PV-systems at an altitude of 530m in central part of Switzerland the same radiation measurements (with no heating of the pyranometer) have been carried out since Jan. 95. Table 2 and Fig. 2 show these data for comparison purposes.

Table 2: Comparison of mean daily irradiation [(kWh/m^2)/d] at ISB Burgdorf (530m)
- Hi,c measured with a calibrated cell,
- Hi,p measured with a pyranometer

Month	Hi,c	Hi,p	Hi,p/Hi,c
Jan-95	1.50	1.60	1.066
Feb-95	2.04	2.14	1.051
Mar-95	3.61	3.76	1.043
Apr-95	3.98	4.15	1.042
May-95	4.83	5.09	1.054
Jun-95	5.01	5.26	1.048
Jul-95	5.65	6.00	1.061
Aug-95	4.49	4.76	1.062
Mean	3.91	4.11	1.053

Fig.2: Monthly Irradiances



At both locations pyranometer readings are usually a few percent higher than reference cell readings (about 4.3% at Jungfraujoch, 5.3% at ISB, thus about 4.8% in the average). This fact has to be considered properly in the following cases:

- When projected energy yields are calculated from irradiation data obtained with pyranometers (usual measuring method of most national weather services). Due to spectral and spatial mismatch, the irradiation usable for a PV array is only the fraction seen by the reference cell, thus a few percent lower. If this fact is not properly considered in simulation programs, predicted energy yields will be to high.
- When values for performance ratio of different PV-plants are compared, it should be indicated, how irradiance measurements were taken. Performance ratio of a PV-plant is usually a few percent lower under the same conditions when irradiance is measured with a pyranometer.

4. HOURLY MEAN VALUES

For the evaluation of the performance of a PV plant the scatter plot of the hourly mean array output power P_a as a function of mean hourly irradiance G_i has a considerable diagnostic value. When all points are grouped close to the ideal line that connects (0,0) with (P_o,1000 W/m^2), the plant is working at its full potential, while points far below this line indicate suboptimal operation.

On the other hand, a plot of the hourly mean values of irradiance G_i measured by the pyranometer vs. the G_i data from the reference cell shows the effects of spectral and spatial mismatch between the two instruments. If the scatter of the points around the ideal line corresponding to the same G_i readings on both instruments is small as compared to the scatter in the (P_a,G_i)-plot, the choice of the type of radiation sensor has little effect on the analysis of the array performance data.

A typical case of such a situation is shown in the figures given below for January 1995. The plots of Pa vs. Gi given in Fig.2a for a reference cell and in Fig. 2b for a pyranometer are almost identical, since the response of both instruments was almost identical, as shown in Fig.2c.

Fig. 2a:
PV Generator Output Power vs. Irradiance
(Reference Cell, January 1995)

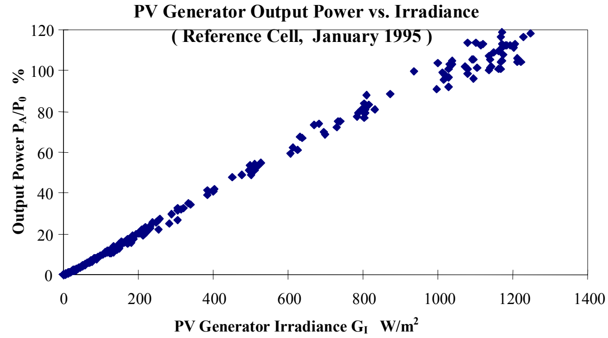


Fig. 2b:
PV Generator Output Power vs. Irradiance
(Pyranometer, January 1995)

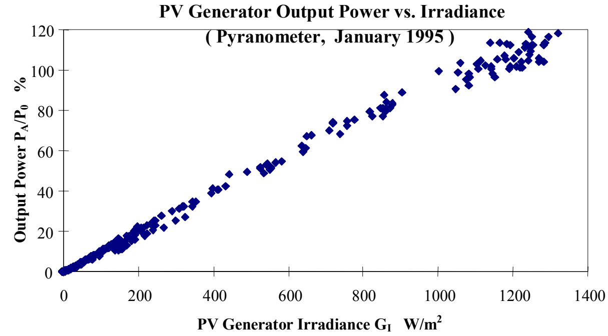
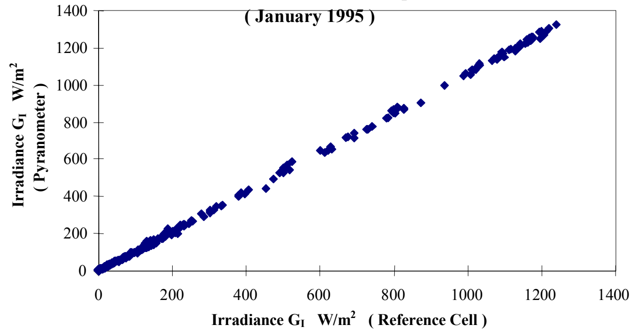


Fig. 2c:
Irradiance Measurements Comparison
(January 1995)



The situation shown in Figs.3a, 3b and 3c for May 1995 is different: as seen from Fig.3c, the different response of the two radiation sensors caused a broadening of the scatter plot and this leads to a broadening in the Pyranometer-Array Power Plot of Fig.3b, as compared with the Cell-Array Power Plot of Fig.3a.

Fig.3a:
PV Generator Output Power vs. Irradiance
(Reference Cell, May 1995)

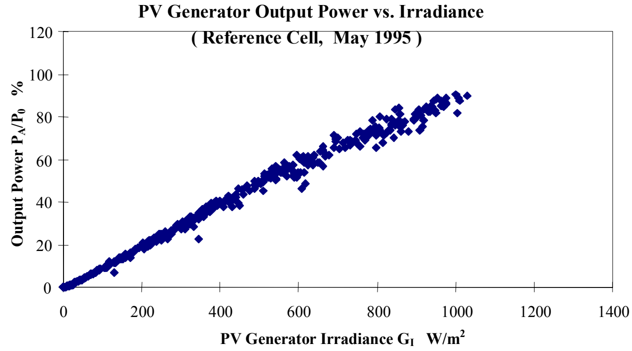


Fig.3b:
PV Generator Output Power vs. Irradiance
(Pyranometer, May 1995)

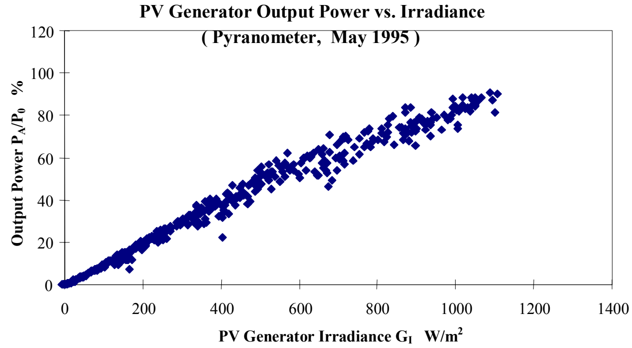
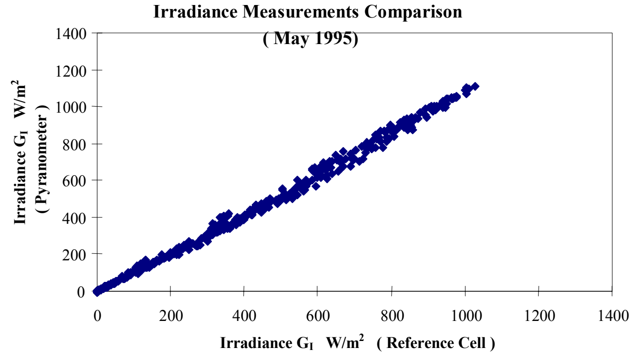


Fig.3c:
Irradiance Measurements Comparison
(May 1995)



However, these effects were relatively small after the proper operation of the heating of the pyranometers since July 1994. Heating was used to avoid snow deposition and ice formation on the dome of the instrument. These effects have been quite visible when the heating was out of order and led to spurious super-ideal array perfor-mances in the Pyranometer-Array Power Plot, as can be seen in the following set of figures from February 1994:

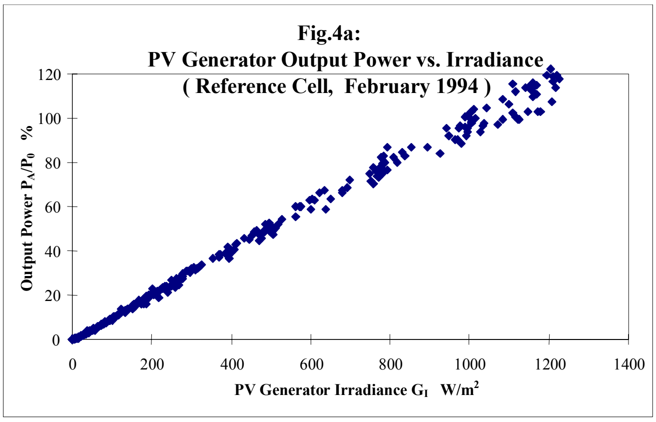


Fig.4a: PV Generator Output Power vs. Irradiance (Reference Cell, February 1994)

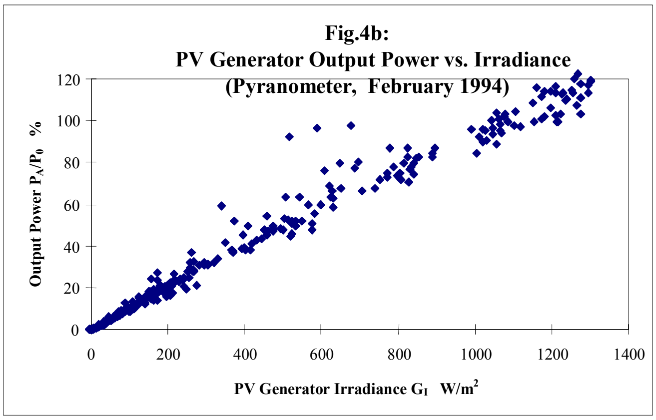


Fig.4b: PV Generator Output Power vs. Irradiance (Pyranometer, February 1994)

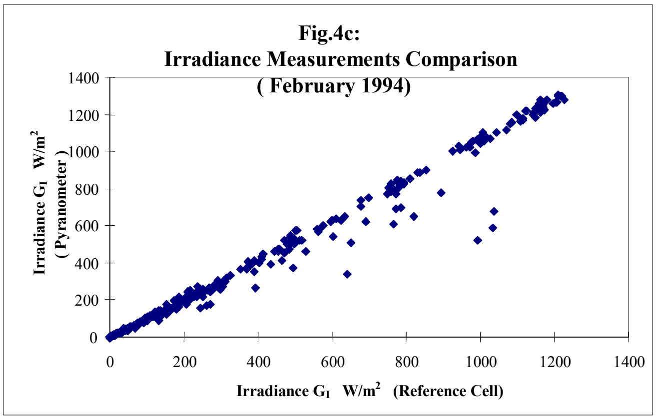


Fig.4c: Irradiance Measurements Comparison (February 1994)

5. CONCLUSION

These results have the following implications on the choice of between pyranometers and Si-sensors for PV monitoring applications:

1. Pyranometers are much more expensive, but also more difficult to use properly by non-specialists (heating of the dome, periodic recalibration, shielding of the low-level signal against noise pick-up). It is easy to make errors with improperly used pyranometers that exceed the range of 2-6%. Thus, under ordinary monitoring conditions (where the accuracy of the data is limited usually within 5%) the calibrated Si-cell is the better choice.
2. Scatter plots of hourly array output vs. irradiance have a much better diagnostic value (as an indicator on how well the available solar energy has been used by the system) when irradiance is measured with a *reference cell, having a spectral response similar to that of the modules*. Therefore cristalline reference cells should be used for cristalline PV arrays and suitable amorphous reference cells for amorphous PV arrays. If a pyranometer (or a cristalline reference cell for an amorphous array) is used instead, spectral mismatch may introduce additional scatter into these plots, and it is impossible to decide whether the observed scatter is due to a weakness in system operation or to spectral effects.
3. When values of performance ratio are given, it must be clearly indicated, if irradiation was measured by a reference cell or a pyranometer, otherwise a fair comparison of different PV-plants is not possible. Performance ratio is usually lower, when irradiation was measured with a pyranometer. If a cristalline reference cell is used for an amorphous array, spectral mismatch may lead to unrealistic values for performance ratio.

Thus it is preferable to use a calibrated Si-cell (of the same type as the cells in the modules of the PV array) as reference device for irradiance measurements for PV plant monitoring.

REFERENCES

[1] H. Haeberlin and Ch. Beutler: „Highest Grid Connected PV Plant in the World at Jungfraujoch (3454m): Excellent Performance in the First two Years of Operation“. Proc. 13th EU PV Conf. Nice 1995.