1. Normalized Energy Yields and Losses

Definition of the normalized quantities \( Y_r \) (Reference Yield), \( Y_a \) (Array Yield), \( Y_f \) (Final Yield) as well as \( L_c \) (Capture Losses), \( L_s \) (System Losses) and \( P_r \) (Performance Ratio) already allows a detailed analysis (see table 1). Annual statistics (with monthly values), monthly statistics (with daily values) and even daily statistics (with hourly values) in tabular form or by diagrams can be generated. By indicating the performance ratio on top of each bar, the information contained in bar graphs can be considerably increased. With such diagrams a direct comparison of different PV plants and a fast recognition of some malfunctions is possible.

2. Normalized Quantities for Power and normalized Daily Diagram

If the storage interval of the data is less than one hour, average values for power and irradiation (e.g. 5-minute values) can also be normalized by dividing them by the PV-generator power \( P_0 \) resp. irradiance \( G_0 = 1\text{kW/m}^2 \) at STC. These new normalized instantaneous quantities are described with small letters \( y_r, y_a, y_f \) and \( p_r, p_s, p_f \) analogous to the corresponding energy yields. With these quantities a normalized daily diagram can be drawn, allowing a much more detailed analysis of system performance. Such normalized instantaneous quantities are also very useful for on-line error detection by using data picked up very frequently, e.g. every second.

3. Splitting the Capture Losses

If not only electrical quantities but also solar cell temperature are measured, \( L_c \) resp. \( L_f \) can be split into:
- thermal capture losses \( L_{cT} \) resp. \( L_{fT} \) (because the cell temperature is usually higher than 25°C)
- miscellaneous capture losses \( L_{CM} \) resp. \( L_{CM} \) (wiring, string diodes, low irradiance, partial shadowing, dirt accumulation, snow-covering, inhomogeneous irradiance, mismatch, maximum power tracking errors etc.)

In a grid connected PV plant a malfunction causes a remarkable rise of \( L_{CM} \) resp. \( L_{CM} \). These quantities are very good indicators for system problems. Well planned and realized plants normally show little \( L_{CM} \) values.

In order to calculate \( L_{CT} \) and \( L_{CM} \), the temperature corrected reference yield \( Y_r \) resp. the temperature corrected irradiance \( y_a \) must be introduced. The power of a solar generator is temperature-dependent (the temperature coefficient is \( c_T = 0.0044/K \) with crystalline cells). An ideal solar generator with nominal power \( P_0 \) (at STC), solar cell temperature \( T_a \) and irradiance \( G_0 = 1\text{kW/m}^2 \) operated in the maximum power point (MPPP) will generate the temperature corrected nominal solar generator power

\[
P_{PT} = P_0[1-c_T(T_a-T_{STC})] \quad \left(T_0 = \text{STC-temperature} = 25^\circ\text{C}\right).
\]

Thus the new quantities can be calculated as

\[
y_r = y_r^T = \frac{y_r}{y_r^T} = \frac{y_r}{y_r^T} \quad \left(y_r^T = y_r^T - c_T y_r^T \right)
\]

By integration of these values, daily, monthly or yearly values of \( Y_r, L_{CT} \) and \( L_{CM} \) can be calculated.

In addition the following useful ratios can be defined:

- \( k_r = y_r/y_r^T \) (temperature correction factor)
- \( k_a = y_a/y_a^T \) (generator correction factor)

For grid connected systems:

\[
n_i = y_i/y_a \quad \text{(inverter efficiency)}
\]

\[
\begin{align*}
Y_r &= \frac{H_f}{G_0}, \quad Y_r \text{ is equal to the time which the sun has to shine with } G_0 = 1\text{kW/m}^2 \text{ to irradiate the energy } H_f \text{ onto the solar generator} \\
L_c &= \frac{H_f}{P_0}, \quad \text{Losses caused by cell temperatures higher than } 25^\circ\text{C} \\
Y_a &= \frac{E_a}{P_0}, \quad Y_a \text{ is equal to the time which the PV plant has to operate with nominal solar generator power } P_0 \text{ to generate array (DC-)energy } E_a \\
Y_f &= \frac{E_{use}}{P_0}, \quad Y_f \text{ is equal to the time which the PV plant has to operate with nominal solar generator power } P_0 \text{ to generate the useful output energy } E_{use}. \text{ For grid connected plants: } E_{use} = E_{AC}. \\
PR &= \frac{Y_f}{Y_r}, \quad PR \text{ corresponds to the ratio of the useful energy } E_{use} \text{ to the energy which would be generated by a lossless, ideal PV plant with solar cell temperature at } 25^\circ\text{C} \text{ and the same irradiation.}
\end{align*}
\]

Table 1: Definition and meaning of normalized yields and losses with PV plants.
4. Examples of some improved and new Diagrams

4.1 Diagrams for Energy Yields and Losses

Fig. 1: Normalized yearly analysis of ISB's PV plant at Jungfraujoch (3454m) with monthly values of \( Y_f \), \( L_s \), \( L_c \) and PR (referred to effective solar generator power). Irradiance is measured with a reference cell. Partial snow covering of the solar generator in spring causes higher \( L_c \) and lower PR-values.

Fig. 2: Normalized monthly analysis for PV-plant Jungfraujoch for May 1994. Due to the very large snow quantity in spring 1994, one of the two PV generators was covered with snow for a few days. Therefore on these days \( L_c \) values are higher and PR values are lower than on other days without snow coverage.

Fig. 3: Normalized daily analysis for May 23, 1994 with hourly values of \( Y_f \), \( L_s \), \( L_c \) and PR. Hourly values of yields and losses are indicated as kW/kWp resp. without dimension. In early morning, part of the PV generator was covered by snow. Then, after 10:00, the snow was removed, causing a characteristic rise of PR.

4.2 Diagrams for normalized Power Yields and Losses

Using the normalized instantaneous quantities defined in chapter 2 and 3, very useful normalized daily diagrams can be generated. These diagrams clearly indicate operational problems of a PV-system, even if these problems are only sporadic.

Fig. 4: Normalized daily diagram for November 22, 1993 with instantaneous values of \( y_r \), \( y_T \), \( y_a \), \( y_f \), \( L_{CM} \) and PR. This day was a clear and cold winter day without any problems, so \( L_{CM} \) is very small and PR reaches a maximum value of more than 0.95.

Fig. 5: Normalized daily diagram for PV plant Birg/Schilthorn (2670m.) on Jan. 4, 1995. As the PV generator (\( P_0 = 4134 \) Wp) is slightly oversized compared to nominal inverter power, DC power is limited to 3.5 kW between 10:00 and 15:00. In normalized representation, \( y_a \) is limited to 0.85. As \( y_T \) reaches a maximum of 1.13 around noon, \( L_{CM} \) rises at higher irradiance levels up to a maximum of 0.28. The daily value of PR is considerably lower than in fig. 4.

Fig. 6: Normalized daily diagram of PV plant Birg on January 15, 1994. Because of heavy snowfalls part of the generator was covered by snow. After sunrise \( L_{CM} \) is already 0.2 and rises to 0.37 around noon. Energy production is reduced considerably, \( k_G \) is only 66% and PR only 57%. Around 9:55 a short inverter shutdown occurred, probably caused by a voltage transient on the AC side. A similar daily diagram could be observed after a fault in some strings of the PV generator (e.g. defects in diodes, fuses etc.).
With normalized diagrams, an approach to the problems encountered is quite easy by successive reduction of the time interval for which the diagram is generated:

**Fig. 7:** Normalized daily diagram on December 11, 1994 of the PV plant (20kWp) on the western part of ISB's building for the department of electrical engineering. After 15:00 $l_{CM}$ rises slowly owing to shadows creeping up from the lower to the higher module rows. Thus $l_{CM}$ is also a good indicator for partial shadowing of the PV generator.

**Fig. 8:** PV plant Aerni/Arisdorf (53kWp) on May 23, 1993. The inverter obviously had a serious problem with maximum power point tracking. During the day $l_{CM}$ rises very high and $pr$ drops. The daily value of $PR$ is very low, too.

### 5. Methodical analysis of a malfunction by means of normalized diagrams:

(Example with a 8.9kWp grid connected PV plant at Interlaken)

**Fig. 9:** Normalized yearly analysis 1994 for PV plant IBI/Interlaken (with 4 inverters in master-slave configuration). In October, $L_{CM}$ is too high compared to other months, therefore there must be a problem.

**Fig. 10:** Normalized monthly analysis for October 1994. During October 2, a problem occurred. As a consequence, the plant was out of order for two days. On October 5, the plant was switched on with reduced power (2 instead of 4 inverters).

**Fig. 11:** Normalized daily analysis for October 2, 1994. Between 13:00 and 14:00, an inverter defect caused a shutdown of the plant. Energy production dropped to 0 for the rest of the day.

**Fig. 12:** Detailed analysis of the inverter failure with an expanded normalized daily diagram (5 minute average values). At 13:35 there is a maximum power point tracking problem (rise of $L_{CM}$ and drop of $pr$). Around 13:42 the master inverter fails completely with a hardware defect. $y_a$, $y_f$ and $pr$ drop to 0, $L_{CM}$ rises to $y_T$. 

---

**Fig. 13**

13th EU PV Conference on Photovoltaic Solar Energy Conversion, Nice, France, 1995
6. On-line Error Detection

Normalized power and losses can also be used for on-line error detection. If data are measured in very short intervals (e.g. every second), it is quite easy to realize a continuous plant supervision. With this supervision, detection of malfunctions is assured.

This new on-line error detection method is already realized at ISB’s PV test site in Burgdorf. The following figures show two screen printouts of a data acquisition computer:

**Fig. 13:** Screen printout of a data acquisition computer at ISB’s PV test site in Burgdorf: Normalized representation of on-line values.

**Fig. 14:** On-line values of the same plant later at the same day with nearly the same value of $y_r$, but without partial shadowing of the solar generator. The value of $L_{CT}$ is now higher than in the morning ($0.041$ instead of $0.193$). Because of the temperature rise of the solar generator, the temperature ratio of the solar generator is partially shadowed by a part of the building.

7. Discussion and some practical Hints

In many PV arrays there are some differences in module temperatures in the array and between modules and reference cells used for monitoring purposes. Therefore $y_T$ (and consequently $L_{CT}$ and $L_{CM}$) may be slightly influenced by such differences. As in many cases most of the capture losses $L_C$ are caused by a temperature rise compared to STC, it is all the same reasonable to split the capture losses into the (easily explainable) thermal losses $L_{CT}$ and the remaining miscellaneous losses $L_{CU}$ and $L_{CM}$ which may have different reasons, but clearly indicate system deficiencies or malfunctions. As they are difference quantities, they are also quite susceptible to measurement errors.

To reduce these practical problems as far as possible, it is essential to position reference cell and temperature sensors appropriately in a average position in the middle of the array, not at an exposed location on top of the array or even higher on a special meteo mast.

Acknowledgements

Our special thanks go to all the institutions that gave us financial support. The work described in this paper was funded by the Swiss Federal Office of Energy (BEW), Berne and the Office for Water and Energy (WEA) of the canton of Berne. Construction of our PV-plant at Jungfraujoch was sponsored by BEW, VSE (Verband Schweizerischer Elektrizitätswerke), Siemens Solar, Fabrimex Solar and the Railways of Jungfrau Region.

Our thanks go also to the International Foundation Scientific Stations Jungfraujoch and Gornergrat, the owner of the research station at Jungfraujoch, who permitted the use of its building for this project. Our PV-activities in general are also supported by IBB, Burgdorf, BKW Energy AG, Berne, and EWIB, Berne.

Conclusion

With normalized representation of PV system data described above, which was introduced by JRC/Ispra and improved by ISB, a very efficient analysis of PV systems of different size and at different locations is possible. Besides electrical quantities, solar cell temperature should be measured in order to split capture losses $L_{CM}$ into thermal and miscellaneous capture losses.

If data measured in intervals shorter than one hour are available, instantaneous values of power and irradiance can be introduced, allowing a much more detailed analysis of system performance with the normalized daily diagram or even an on-line error detection.

Due to space limitations, only a very short overview of this new method for the analysis of the performance of PV-systems could be given here. A much more detailed introduction and description is given in [2].

References:


