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PERFORMANCE OF 170 GRID CONNECTED PV PLANTS IN NORTHERN GERMANY—ANALYSIS OF YIELDS AND OPTIMIZATION POTENTIALS

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Abstract—Within the German 1000 roof PV programme, about 2000 grid connected PV plants (1–5 kW_p) with a total peak power of 5 MW_p were installed on the roofs of single and two family houses. In the Federal State of Lower Saxony, ISFH has been responsible for the technical inspections and the global monitoring of 172 PV plants up until now. The annual final yields range between 430 kWh/(kW_p*a) and 875 kWh/(kW_p*a) with a mean value of 680 kWh/(kW_p*a). Using the annual in-plane irradiation, we determine annual performance ratios in the range 47.5%–81% (mean 66.5%). A procedure to receive standardized performance ratios is introduced using actual peak powers of the PV modules and inverter-specific efficiencies. Typical curves of monthly values of the performance ratio are recorded. PV plants with low final yields are analyzed with respect to operational failures, partly shadowing effects, and poorness in maximum power point adaptation of some inverters. Optimization potentials are also discussed. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

Existing roofs and facades of buildings have a high area potential for photovoltaic electricity production. In Germany, roofs directed to the South with a 20°–55° tilt angle have the highest annual irradiation. Within the German 1000 roof PV programme, about 2000 PV plants with a total peak power of 5 MW_p have been installed during the years 1991–1994. All the PV generators are mounted onto or integrated into the roofs of single and two family houses (see Fig. 1). Each PV plant has a peak power of 1–5 kW_p and is grid connected. Excess PV electricity is fed into the grid (the utilities pay for 90% of the electricity price). The 1000 roof PV programme was supported by the Federal Ministry for Research and Technology (50%) and the Federal States (20%).

In the Federal State of Lower Saxony, ISFH was responsible for organization of the programme. So far 172 PV plants with a total peak power of 392 kW_p have been installed in Lower Saxony. ISFH inspected them technically. Figure 2 gives a block diagram of a typical PV system. The PV generator consists of numerous standard PV modules (50 W_p) in series and parallel connection. In the junction box the parallel string cables are interconnected to the main DC cable. A DC circuit breaker is installed close to the DC–AC inverter. The DC installation has to be earth and short circuit proof.

ISFH has an extensive database about system designs, used PV modules and inverters, tilt angles and orientations of PV generators, details due to mounting and DC installation, and details due to shade geometry. Furthermore, ISFH takes part in the German long-time monitoring and analyzing programme (L-MAP) within the 1000 roof PV activities. In this programme the Fraunhofer-Institut für Solare Energiesysteme (FhG-ISE, Freiburg) is responsible for the analytical monitoring of 100 selected PV plants in Germany (I-MAP). The Technischer Überwachungsverein Rheinland (TÜV, Köln) and the Forschungszentrum Rossendorf (FZR, Dresden) will technically inspect 100 other PV plants after five years of operation, and ISFH is performing field measurements at PV plants with extraordinary low final yields to analyze the factors of influence.

2. MONITORING

Within a global monitoring programme at each PV plant, three AC electricity counters register the total PV energy, the excess energy fed into and the energy drawn from the grid. In the Federal State of Lower Saxony, 50 PV plants are additionally equipped with solar integrators to obtain in-plane irradiation. Flat silicon sensors of the type NES SI 161 calibrated under standard test conditions (STC) are used. But it should be taken into account that in Germany generally annual irradiation data measured by

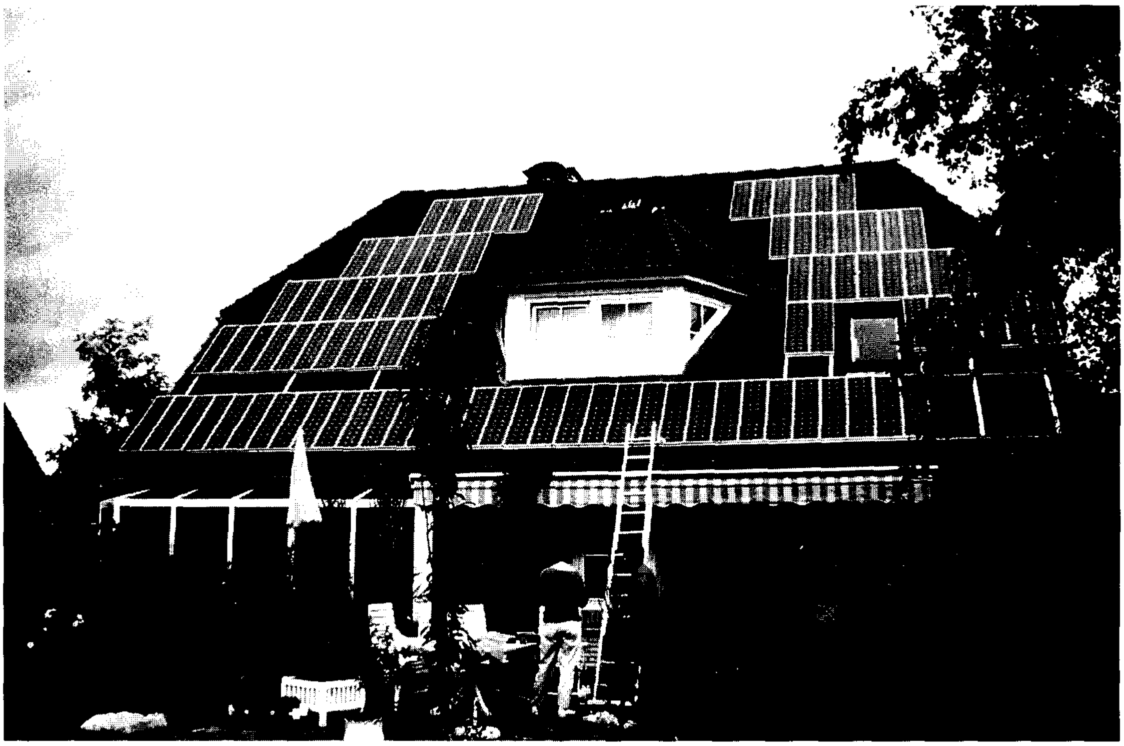

Fig. 1. 5 kW_p PV plant near Hannover.

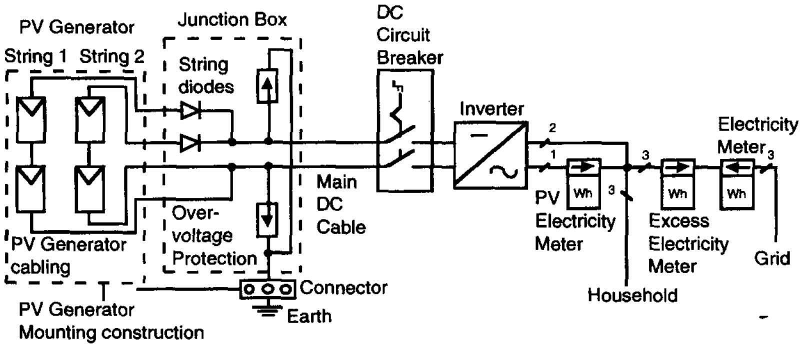

Fig. 2. Block diagram of a typical PV system.

flat silicon sensors deviate from pyranometer data by 3%–7%. The monitoring data of all PV plants are available as monthly sums. They are completed by the house-owners' information about operation failures, repair and maintenance.

3. FINAL YIELDS AND PERFORMANCE RATIOS

3.1. Statistics of final yields

To compare the PV systems independently from their size, the final yield Y_f is used. It is the annual, monthly or daily PV energy output E_{PV} divided by the nominal power $P_{PV,nom}$ of the PV generator:

$$Y_f = E_{PV}/P_{PV,nom}. \qquad (1)$$

Usually $P_{PV,nom}$ is the power quoted on the PV module's datasheet. However, often the actual peak power of the PV modules is lower because the manufacturers have different practices in standards of quality control, in quoting mean or minimum power, and in giving limits of tolerance.

In Lower Saxony, 144 PV plants were operating from January to December 1994. Figure 3 shows the frequency distribution of their annual final yields. In 1994, Y_f varied from 430 to 875 kWh/(kW_p*a) with a mean value of

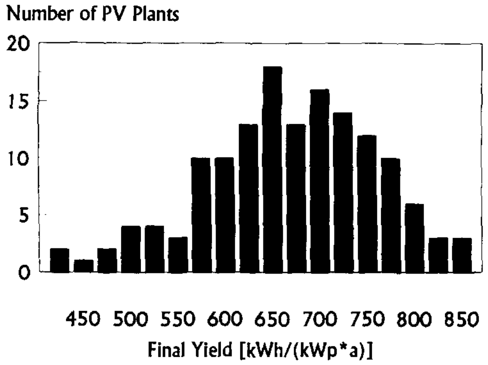

Fig. 3. Frequency distribution of the annual final yields from 144 PV systems in 1994.

680 kWh/(kW_p*a). Compared to previous years—with lower numbers of PV plants—the mean value differs significantly (in 1992: 731 kWh/(kW_p*a) (Decker *et al.*, 1993), in 1993: 658 kWh/(kW_p*a) (Jahn *et al.*, 1994)).

The PV energy output is used directly by the owner's household or fed into the grid. Depending on the nominal power of the PV generator (mean value: 2.3 kW_p) and on the electricity consumption (mean value: 4300 kWh/a), direct use fractions from 20% to 60% are obtained.

Under system analytical aspects, the final yield of a PV plant is of limited significance because the mean annual global irradiation all over Lower Saxony varies from year to year and—due to a single PV plant—the annual in-plane irradiation varies with location, array tilt angle and orientation.

Figure 4 shows the frequency distribution of the annual in-plane irradiation of 42 PV plants in 1993 and 1994. At single locations it varies from 880 to 1165 kWh/(m^2*a) with mean values of 990 kWh/(m^2*a) in 1993 and 1054 kWh/(m^2*a) in 1994.

3.2. *Forecasting of final yields*

A correlation between a PV system's final yield and the in-plane irradiation has to be given. Figure 5 shows an energy flow chart on the assumption of annual irradiation of 1000 kWh/(m^2*a).

The nominal power $P_{\mathrm{PV,nom}}$ of a PV module or its standard efficiency $\eta_{\mathrm{PV,STC}}$—due to the module area A_{mod}—are momentarily determined in the laboratory or outdoors under standard test conditions (STC, $G_{\mathrm{STC}} = 1000\ \mathrm{W/m^2}$):

$$\eta_{\mathrm{PV,STC}} = P_{\mathrm{PV,nom}}/(G_{\mathrm{STC}}{}^{*}A_{\mathrm{mod}}). \qquad (2)$$

When the PV module mounted onto the roof is operating throughout a whole year, the real meterological conditions and module temperatures have to be considered. This site- and orientation-specific phenomenon is described by the module's annual efficiency under realistic reporting conditions $\eta_{\mathrm{PV,RRC}}$. This can be determined by the PV module's energy output $E_{\mathrm{PV,gen}}$ and by the in-plane irradiation H_{A}:

$$\eta_{\mathrm{PV,RRC}} = E_{\mathrm{PV,gen}}/(H_{\mathrm{A}}{}^{*}A_{\mathrm{mod}}). \qquad (3)$$

Compared with $\eta_{\mathrm{PV,STC}}$, the annual $\eta_{\mathrm{PV,RRC}}$ is decreased by 10%–14% due to the occurence of low irradiance levels, high module temperatures, high reflection losses at flat incidence angles and deviations from AM 1.5 spectrum (Decker *et al.*, 1993). Additional energy losses in PV array due to pollution and power mismatch have to be considered. Most manufacturers quote the nominal power of the PV module with a tolerance limit of 10%.

System energy losses are mainly caused by the DC installation (cables, string diodes, switches, fuses, etc.) and by the inverter(s). The most common inverters were tested in the laboratory with respect to their efficiency curves (Vaaßen *et al.*, 1993). Assuming an optimal matching between the nominal power of inverter and PV generator, annual inverter energy losses of 10%–16% can be estimated (Decker *et al.*, 1993).

Taking all PV array and system energy losses in Fig. 5 into account, the annual final yield of a 1 kW_p grid connected PV system can be forecast in the range 600–790 kWh/a.

3.3. *Statistics of performance ratios*

The performance ratio PR is a quantity for the technical quality of (grid connected) PV systems. It allows the comparison of PV plants independently from their location, tilt angle and orientation and their nominal power. The PR is defined as the ratio between the final yield Y_{f} and the in-plane irradiation H_{A}:

$$\mathrm{PR} = (Y_{\mathrm{f}}{}^{*}G_{\mathrm{STC}})/H_{\mathrm{A}} = (E_{\mathrm{PV}}{}^{*}G_{\mathrm{STC}})/(P_{\mathrm{PV,nom}}{}^{*}H_{\mathrm{A}}). \qquad (4)$$

For example, looking at a 2 kW_p PV plant with a PV energy output $E_{\mathrm{PV}} = 1650$ kWh/a and an in-plane irradiation $H_{\mathrm{A}} = 1100$ kWh/(m^2*a), a final yield $Y_{\mathrm{f}} = 825$ kWh/(kW_p*a) corresponds to a performance ratio PR of 75%.

Figure 6 shows the frequency distribution of annual performance ratios for 42 PV plants in Lower Saxony. In 1993 the annual PR ranged

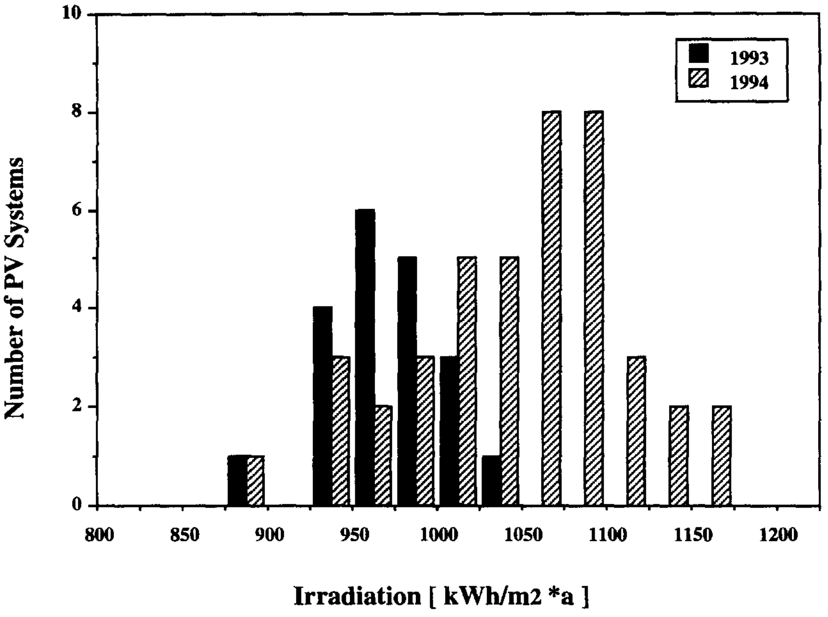

Fig. 4. Frequency distribution of the yearly sum of in-plane irradiation monitored at 26 (1993) and 42 (1994) PV systems with solar integrators.

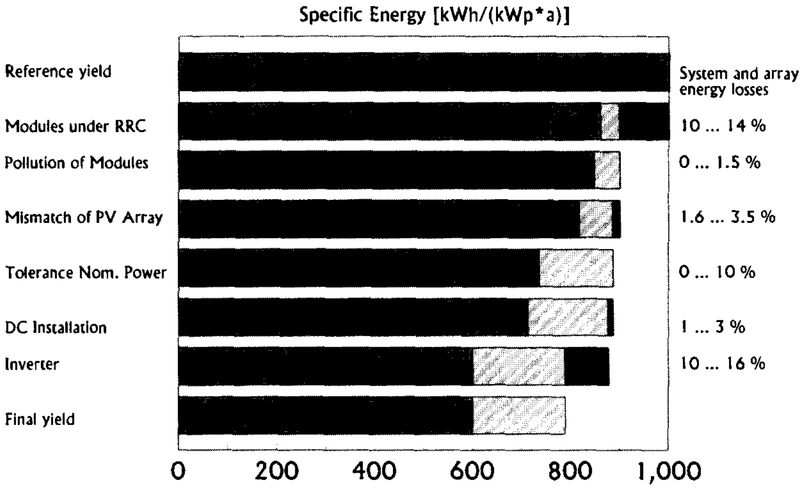

Fig. 5. Energy flow chart of a grid-connected PV plant.

from 43.9% to 82.5%, and in 1994 from 47.5% to 81.1%. There is consistency in the mean values of 1993 (67.5%) and 1994 (66.5%).

Using the forecasting in Fig. 5, the annual PR of the 42 PV systems in Lower Saxony should vary between 60% and 79%. In 1994, most PV plants were operating at the estimated performance. The higher PR of one PV plant is obviously caused by non-reliable data of the AC electricity counter due to an interaction with the harmonics of the inverter. The lower PR of seven PV plants can only partly be explained by long-time failures of PV system components (e.g. inverter).

3.4. Standardized performance ratios

To obtain a more detailed understanding of system performance, we introduce a standardized performance ratio $\mathrm{PR_{ST}}$. Using the PR definition

$$\begin{aligned}\mathrm{PR} &= \eta_{\mathrm{sys}}/\eta_{\mathrm{PV,STC}} \\ &= \eta_{\mathrm{PV,RRC}}{}^{*}\eta_{\mathrm{inv}}{}^{*}\eta_{\mathrm{residualsys}}/\eta_{\mathrm{PV,STC}} \qquad (5)\end{aligned}$$

where η_{sys} is the PV system efficiency, η_{inv} is the inverter efficiency and $\eta_{\mathrm{residualsys}}$ is the efficiency of the "residual system" (pollution and mismatch losses due to PV modules, ohmic losses

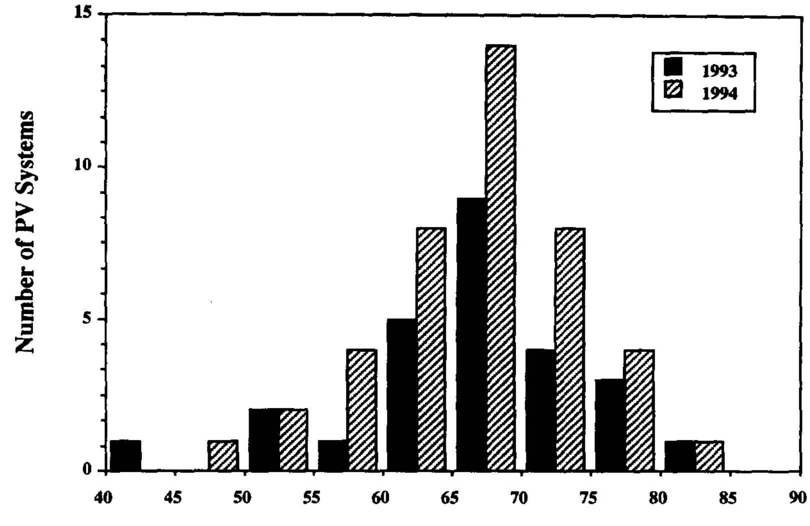

Fig. 6. Frequency distribution of the annual performance ratios of 26 (1993) and 42 (1994) PV plants.

of DC installation), the standardized PR_{ST} is derived by multiplying by:

(1) the ratio between the PV module's nominal power $P_{PV,nom}$ quoted in its datasheet and its mean actual peak power $P_{PV,act}$ (received by random power measurements of module samples and by analysis of detailed monitoring data in L-MAP) (Kiefer, 1994);

(2) the ratio between the highest-known annual inverter efficiency $\eta_{inv,opt}$—using optimal power matching between inverter and PV generator—and the efficiency η_{inv} of the used inverter and power matching (eqn (1)):

$$PR_{ST} = PR^*(\eta_{PV,STC}/\eta_{PV,act})^*(\eta_{inv,opt}/\eta_{inv})$$

$$= \eta_{PV,RRC}{}^*\eta_{inv,opt}{}^*\eta_{residualsys}/\eta_{PV,act} \quad (6)$$

Often a low performance ratio PR is caused by deviations of the quoted power rating of the PV modules (e.g. $P_{PV,act} = 45\ W_p$ compared with $P_{PV,nom} = 53\ W_p$) and a low inverter efficiency ($\eta_{in} = 85\%$ compared with $\eta_{inv,opt} = 90\%$). Continuing this example, a low $PR = 62\%$ corresponds to a standardized $PR_{ST} = 77\%$.

With standardized PR_{ST}, all PV plants are referred to the module's actual peak power and to the most efficient inverter with optimal power matching. Additionally—in case of long-time failures of system components—the PV energy output is extrapolated to one year of trouble-free operation. Then the forecast range of standardized PR_{ST} is smaller (71%–79%) and more meaningful.

4. LOW YIELD ANALYSIS AND OPTIMIZATION POTENTIALS

Figure 7 compares the frequency distributions of the annual PR to the standardized PR_{ST} for 42 PV plants in Lower Saxony. In 1994, most PV plants operate in the predicted narrow range of annual PR_{ST}. Seven PV plants with $PR_{ST} < 71\%$ are analyzed in more detail. Their bad performance can be explained by:

(1) long-time partial shading of PV array (three PV plants),

(2) module strings in off-circuit mode caused by loosening of their clamped connections in the junction box (three PV plants),

(3) long-time poor maximum power voltage adaptation of the inverter (one PV plant).

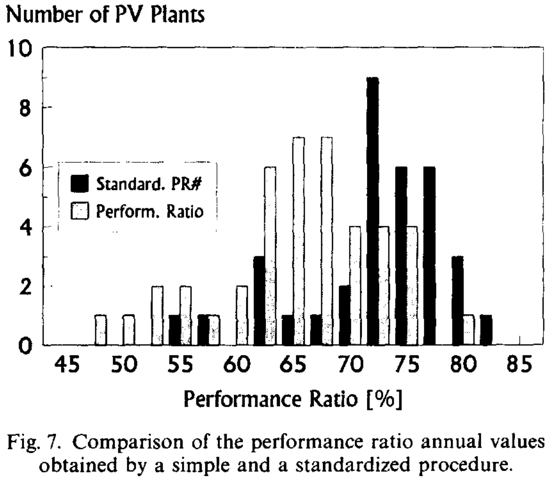

Fig. 7. Comparison of the performance ratio annual values obtained by a simple and a standardized procedure.

Three PV systems seem to have a good performance ($PR_{ST} > 79\%$). This could probably be due to

(1) non-reliable data of the AC electricity counters or of the solar integrators,

(2) PV modules of a high-quality series that have a significantly higher actual peak power than mean value of this module type.

4.1. Monthly means of performance ratio

Important tools for the assessment of PV plants with low final yields are the monthly means of performance ratio during the course of the year. Figure 8 shows the monthly means of the in-plane irradiation for 42 PV systems in Lower Saxony with a maximum in June/July and a minimum in December/January. Figure 9 shows the monthly means of performance ratio in 1993 and 1994. The PR mainly depend on meteorological effects. Low PR in winter are due to low irradiance values, low incidence angles, and partial load characteristics of the inverters. In some cases they are due to shading effects and snow coverage. Higher PR in March/April (68.8% in 1994) and October (69.6% in 1994) are due to lower module temperature in comparison to the summer months.

4.2. Shading effects

Shading due to nearby vegetation or buildings leads to lower final yields and performance ratios PR than predicted. Shading is responsible for the low PR in three of seven PV plants with a $PR_{ST} < 71\%$. Particularly in winter months,

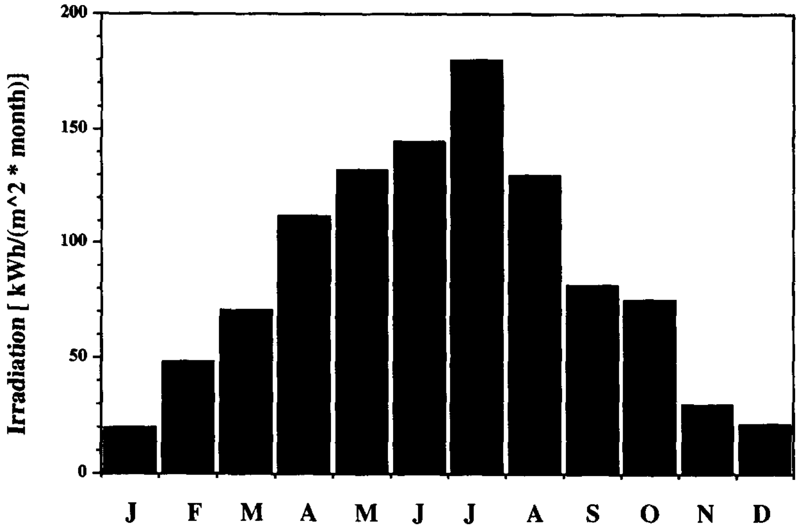

Fig. 8. Monthly means of the in-plane irradiation at 42 PV plants (1994).

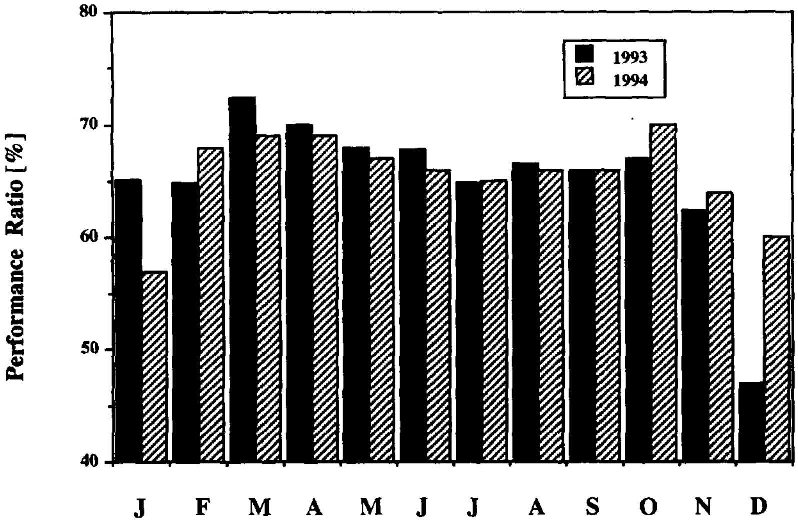

Fig. 9. Monthly means of the performance ratios of 26 (1993) and 42 (1994) PV systems.

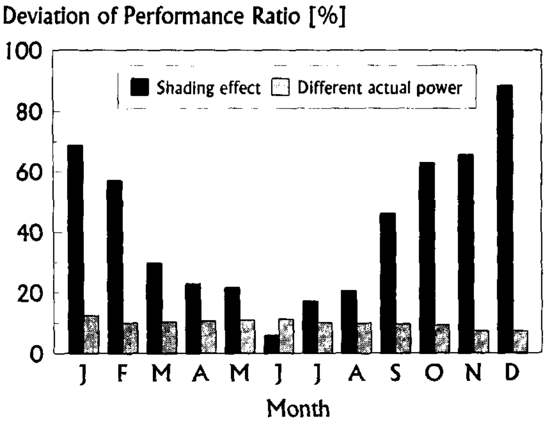

Fig. 10. Effects of shading and low actual peak power on the monthly performance ratios using two identical PV systems.

shading has a strong effect on the PR values. In Fig. 10 the deviation of the monthly PR is shown comparing two PV systems of identical PV module type, inverter and system design, but one of them being strongly shaded. Losses in annual PR of 30% can be attributed to the shading effect.

Final yields of partly shaded PV systems can be improved substantially, if shading is avoided or—in larger PV plants—limited to a small number of strings. To optimize yields, more attention must be paid to shading effects during planning and installation of PV systems.

Also, deviations of the quoted module power rating can cause low PR values if the actual peak power of the installed PV modules is significantly lower. In Fig. 10, two PV systems of identical module nominal power, inverter and system design, but of different accuracy in module quotation are compared with one another. It can be seen that the deviation of the monthly PR is constant throughout the whole year.

5. CONCLUSIONS

Global monitoring data concerning the performance of grid connected PV systems in Lower Saxony are available. A well-designed PV system on a roof top may obtain final yields of 750–850 kWh/(kW_p*a). Due to array and system losses, typical annual performance ratios of 60% and 79% can be expected. They are dependent on the efficiencies of the inverters, on the quality of system design, and unfortunately on deviations between the quoted module power rating and the actual peak power. Labeling of the actual peak power for each PV module is recommended to the manufacturer.

The introduction of standardized performance ratios is useful to identify PV plants of low performance without doubt. Comparisons of the monthly values of performance ratio are helpful to detect the short-term (e.g. off-circuit module strings) or the long-term (e.g. shading) influencing factors of low final yields. At ISFH, detailed field measurements have been initiated to analyze low final yields and to gain experience for further optimization of grid-connected PV systems.

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