PERFORMANCE ANALYSIS AND RELIABILITY OF GRID-CONNECTED PV SYSTEMS IN IEA COUNTRIES

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ABSTRACT

This paper presents operational performance results of grid-connected PV systems, as collected and elaborated for the Photovoltaic Power Systems Programme of the International Energy Agency (IEA). Performance ratios (PR) obtained from 334 PV installations in 14 different countries are compared and discussed. In Germany, there is a significant rise of PR between early installations in the nineties and new installations. For Switzerland, BIPV and other types show high PR > 0.80, but average PR values lower than expected were obtained. For Japan, lessons learnt from the current monitoring programmes are used to improve PV system performance showing constant performance at high level. As an outcome of this work, reliable and worldwide monitoring performance data and results are available for future developments of financing schemes (e.g. feed-in-tariffs) in order to stimulate the PV market.

1. INTRODUCTION

As a part of the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS), a working group is collecting and analysing operational data of photovoltaic plants in various system techniques. The objective of this joint project is to provide technical information on the operational performance, reliability and sizing of PV systems and their subsystems. Participants of this group, Task 2, have developed a database to accommodate technical and operational data of different types of systems operating at different climatic conditions and adapted to various applications [1]. The database programme (47 MB) can be downloaded from the website at www.task2.org and is available on CD-ROM.

At present the Performance Database of IEA-PVPS Task 2 contains high quality data of 372 monitored PV plants with an installed capacity of 12 MWp located in 15 IEA countries (s. Table I). Most of the monitoring data have been gathered under various national demonstration programmes in the IEA-PVPS member countries: e. g. Austrian Rooftop Programme, French Rural Electrification Programme, EU Thermie Programme, German 1 000-Roofs-PV-Programme and Sun-at-school programme, Italian Roof-topprogramme, Japanese Field Test Program and Residential Monitoring Program as well as Swiss PV promotion programmes. There has been an increasing trend for demonstration programmes to focus on grid-connected PV systems. Particular complete statistics are available from 334 grid-connected PV systems ranging from small decentralized systems (PV roof tops), dispersed systems (BIPV, sound barrier) to centralized systems (PV power plants).

Table I Overview of collected monitoring data in terms of countries, systems and their installed PV power included in the IEA-PVPS Performance Database

Country	Number of PV systems	Nominal power of all plants [kWp]	Monthly monitoring datasets
Austria	25	82.5	495
Belgium	1	5.2	36
France	9	6.4	204
Germany	109	1291.3	4634
Israel	7	13.7	141
Italy	30	5004.5	912
Japan	94	2671.3	2542
Mexico	3	5.2	39
Netherlands	24	536.6	500
Poland	1	1.0	23
Portugal	1	5.0	20
Spain	1	42.0	24
Sweden	3	62.5	98
Switzerland	62	1963.9	3468
United Kingdom	2	112.7	48
Sum	**372**	**11803.8**	**13184**

The analysis of PV system performance is based on the European Guidelines, Document B [2], and the IEC Standard 61724 [3]. Key parameters for evaluation of PV system performance are energy yields , efficiencies and performance ratio. The most appropriate performance indicators of grid- connected PV systems are final PV system yield (Y_f), reference yield (Y_r) and performance ratio (PR) as defined in [2], [3] and [4]. The performance ratio PR is the ratio of PV energy actually used to the energy theoretically available (i.e. Y_f / Y_r).

2. OPERATIONAL PERFORMANCE OF GRID-CONNECTED PV SYSTEMS

From the performance analysis of 334 grid-connected PV systems supplied by the Performance Database of Task 2, it was learnt that the average annual yield (Y_f) fluctuates only slightly from one year to another and has typical average annual values for one country (700 kWh/kWp for Germany and the Netherlands, 790 kWh/kWp for Switzerland, 864 kWh/kWp for Italy, 990 kWh/kWp for Japan and up to Y_f = 1 840 kWh/kWp for Israel). However, there is a considerable scattering around these average values for individual systems ranging from 400 kWh/kWp to 1 030 kWh/kWp in Germany and from 450 kWh/kWp to 1 400 kWh/kWp for plants in Switzerland [5].

Figure 1 shows the distribution of annual performance ratios calculated from 1142 annual datasets of 334 grid-connected PV systems operating during 1992 to 2002, which are grouped into two installation periods. Early installed PV systems (1983-1995) have their maximum in the PR range of 0.65 to 0.7 and an average mean PR of 0.66 for 725 annual performance data. The newer installations

1996-2002 have their maximum in the range of 0.75 to 0.8 with an average value of PR = 0.70 for 417 annual datasets. This is a significant rise in PV system performance and reliability, which the systems in 14 countries have gained.

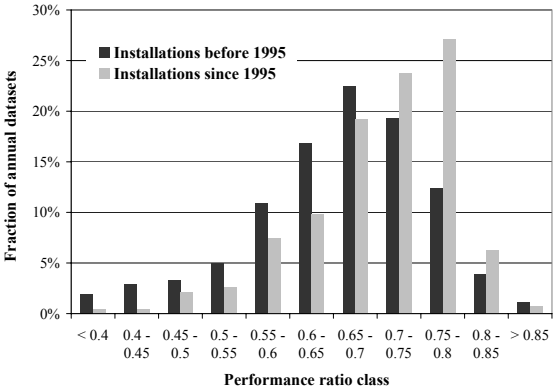

Figure 1 Distribution of annual performance ratios of 334 grid-connected PV systems (1142 annual datasets) in 14 countries for two different installation periods

3. TRENDS IN PV SYSTEM PERFORMANCE

This section will give representative performance results for selected PV systems in Germany, Switzerland and Japan. Detailed results of all systems will be given in [6].

3.1 GERMANY

The 78 PV early systems under investigation are part of the 1000-roofs-PV-programme in Northern and Eastern Germany and they were installed between 1991 and 1994. These residential roof top systems have an installed capacity between 1 and 5 kWp (average 2.5 kWp) and operate since more than ten years. Global monitoring data are available from the standard monitoring and evaluation programme for the years 1993 to 2000. All PV rooftops are equipped with calibrated silicon sensors to measure the in-plane irradiation at the site of the PV arrays.

Figure 2 shows the annual performance ratios of the 78 PV systems operating since the early nineties. The annual PR differs significantly from plant to plant and shows a broad range for all operating years. The average annual PR of 0.67 in 1993 drops to an average value of 0.60 in 2000. The average performance values clearly show negative tendency. Energy yields and PR have been reduced by 11 % between 1993 and 2000.

The registered failures at 21 PV systems during ten years of operation show that defects and problems were first decreasing (1992 to 1995), but started to increase during last years (1999 and 2000). Considering a total number of 47 failures in 210 operational years, a statistical failure will occur every 4.5 years per plant. Inverters are contributing with 63 %, PV modules with 15 % and other system components with 23 % to the total failures.

The 58 new installations built between 1997 and 2001, are different in size (1 kWp to 1 MWp), in their application (residential system, power plant, school programme) and in mounting (roof top, freestanding, BIPV). In Figure 2 the trends of the annual PR are compared for the early and the new installations. For the new German installations significantly higher values are obtained between 1998 and 2002. Mean annual PR values between 0.73 and 0.76 are found resulting in an average mean annual PR of 0.74 for all 58 new installations. Furthermore, the spreading of annual PR values has been reduced during 1998 and 2002 as a result of improved quality of the new systems.

It can be concluded that a negative tendency in terms of performance and yields was observed for these early installations (1991-1994) from the rooftop programme during eight years of operation. Learning experiences were made for early inverter developments that had led to frequent inverter failures, which resulted in significant reductions of the annual energy yields for some PV plants.

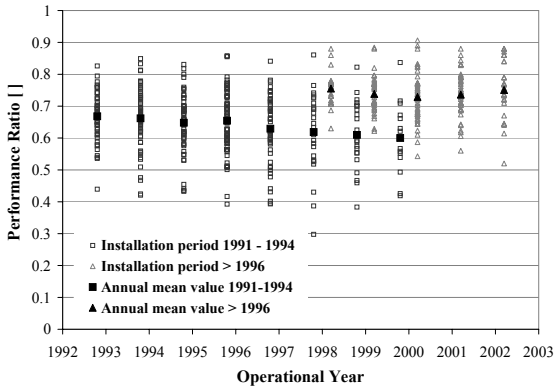

Figure 2 Trends of annual performance ratios of 78 residential PV systems installed between 1991 and 1994 in Germany compared to 58 German PV systems installed since 1997

New PV installations (after 1997) in Germany revealed that they reach higher component efficiencies (e.g. inverter) and higher performance ratios (> 0.80). The high level of average annual PR (0.74) and no change of average PR in five operational years (1998-2002) indicate that the quality of the newer systems in Germany has clearly increased.

The frequency distribution of the 78 early and the 58 new German installations gives the same result. For early systems the PR spread is between 0.4 and 0.85 with an average PR of 0.64. The PR spread of new systems lies between 0.50 to 0.85 with an average PR of 0.74. Here, a significant rise in mean annual PR of 15 % was found.

3.2 Switzerland

The 62 grid-connected demonstration plants in Switzerland are characterized by a broad range of applications (building integrated PV, roof top, sound barrier, power plant) and by analytical monitoring campaigns. PV systems of 1 to 560 kWp were continuously installed between 1989 and 1999 and monitored during 1991 and 2002. The average annual performance of 62 grid-connected plants and 308 operational years results in PR of 0.69 and avarage availability higher than 95 %. The spread of annual PR values per year is rather high, e.g. in 2001 between 0.45 and 0.82.

Well performing plants have reached annual PR of 0.82 in conjunction with annual inverter efficiency of higher 97 %. From the 62 Swiss systems under investigation, reduced performance factors are identified:

- System and component failures are the main reason for reduced PR values
- High module temperatures of BIPV and facades have a negative impact on yields and PR (energy losses 0 % up to 10 % [7])
- Partial shading of the PV array
- Unfavourable array orientations given by the building structure play a negative role for the energy yield.

For some BIPV, design criteria were focussed to building requirements and architectural design criteria, which has led to lower yields and performances than expected. BIPV substituting the building skin has a double value and must fulfil the compromise between architectural building aspects and technical performance of the system.

3.3 Japan

The performance data of 76 Japanese PV systems were gained from different PV programmes in Japan. The Field Test Program was initiated in 1992. Between 1992 and 2000 more than 507 PV systems and 13.5 MWp were installed. The target systems of this on-going programme are public facilities for installations years 1992 to 1996 and industrial applications for installations years 1997 and afterwards. The capacities of the systems are ranging from 10 to 200 kWp.

The Residential PV Monitoring Program is a very large promotion programme and was initiated in 1994. Between 1994 and 2000 more than 58 600 PV systems and 216.5 MWp were installed, and these figures are estimated to be over 100 000 PV systems and 400 MWp in March 2003. The target systems of this epoch-making programme are residential PV systems, which are scattered all over the 47 prefectures in Japan. A detailed monitoring programme started in 1997 by JQA and 100 residential PV systems were on-line monitored by the end of 2000.

The annual performance ratio of the systems from the Field Test Program shows nearly constant mean annual PR values between 0.74 (1995) and 0.72 (2001). The average PR of all 44 Field Test plants (99 annual datasets) is PR = 0.72 and shows well performing systems. But the distribution of annual PR within one operational year is rather broad (e.g. PR = 0.55 to PR = 0.83 in 2001). The existence of partial shadings and MPPT mismatch in some systems are considered to be the most common reasons for this broad distribution in PR values.

During 1995 and 2001, no significant changes (decrease) are identified in the performance indices of the Field Test systems. The nearly constant annual PR values indicate that the monitoring has a positive effect on the PV system performance, e.g. resulting in the prompt exchange of faulty system components and thus improving the performance. Slightly smaller values in PR were found in the systems installed in 1996 and afterwards. One assumed reason is the change in policies of module manufacturer‘s rating for their products. More true ratings are adopted in recent years. The increase in BIPV having design-oriented arrays and multi-oriented arrays may be the other reasons for these trends.

The performance data for the Residential Monitoring Program were split into two groups: PV systems with multi-oriented PV array were separated from the ones with single oriented PV array. Figure 3 shows the PR development between 1998 and 2002. For the 10 residential PV systems with single oriented PV array, the annual PR values range from 0.71 (1998) to 0.72 (2002) with an average PR value of PR=0.71. For the 15 residential PV systems with multi-oriented PV arrays, the annual PR values range from 0.67 (1998) to 0.65 (2002) with an average PR value of PR = 0.67 and is clearly lower than expected.

The difference in performance between these two groups of residential systems can be understood mainly by the fact that the irradiation is measured only at one PV array plane (generally south facing array) which may give rise to presumably lower PR values. The average annual PR values of PV systems from different Japanese programmes show a constant behaviour at a high level indicating high quality of PV systems operation.

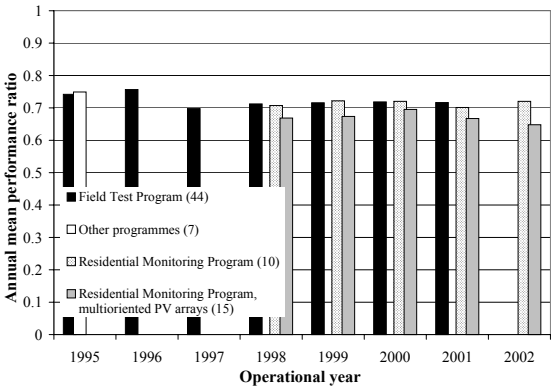

Figure 3 Trends of annual performance ratios of 76 grid-connected PV systems installed within different PV promotion programmes in Japan between 1984 and 2000 (number of systems in brackets)

4. RELIABILITY OF PV SYSTEMS

How reliable are PV systems and their components? To investigate the trends of system availabilities, 17 Italian systems were analysed. The 17 systems with capacities of kWp to MWp and from different programmes were installed between 1983 and 2002. Figure 4 shows the annual system availability as a function of PR. A linear correlation between PR and availability is given for the selected systems indicating that a low performance is correlated with low availability (= high failure rate). This is true for some of these Italian systems, which obtained low PR values due to frequent failure rates of components (inverter, DC components). In general, high system availability guarantees high yields and PR. The spread of PR values at 100 % system availability (Fig. 4) indicates that further factors have an impact on the performance (inverter efficiency, shading, array orientations, high module temperatures).

Figure 5 shows the distribution of annual system availability for 116 systems in Germany, Switzerland and Italy

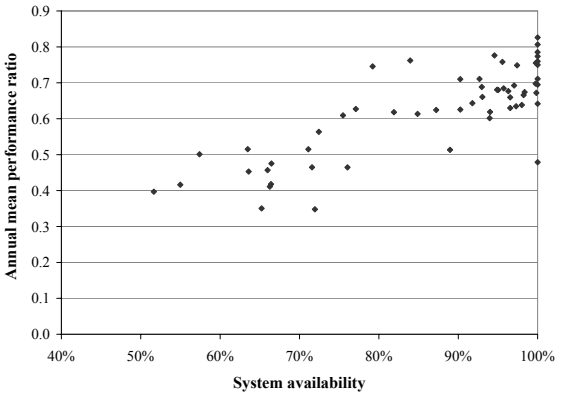

Figure 4 Correlation of annual performance ratio and of annual system availability for 17 grid-connected PV systems installed in Italy between 1983 and 2000 and operating from 1992 to 2002

grouped into two different installation periods. For the 82 systems installed before 1995, the average annual availability is 94.6 % compared to 95.9 % for the 34 new installations. While this modest increase of 1-2 % in system availability was found for the 116 systems and two periods, the annual PR increased by 5 % for the same systems and periods. Thus the rise in PR is mainly due to improvements such as higher efficiencies of components, true module ratings and operation without obstacles such as shadings mismatch and module temperature losses. It was further observed that the system availability is generally higher for systems, which are intensively monitored.

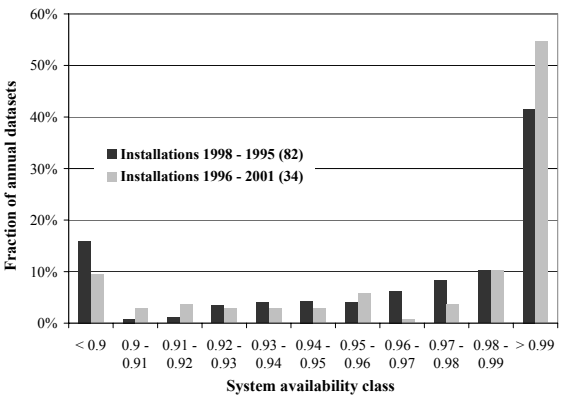

Figure 5 Frequency distribution of annual system availability of 116 grid-connected PV systems from Germany, Switzerland and Italy (488 datasets) operating from 1992 to 2002 for two different installation periods

5. CONCLUSIONS

From the performance analysis of 334 grid-connected PV systems in the IEA-PVPS Task 2 database, a clear tendency of improved performance was found for new PV installations. Better inverter efficiencies, higher system availabilities and realistic PV module ratings are identified as reasons for it. At the same time, the broad spread of annual PR has decreased, which is due to system and component failures, shading effects, MPPT mismatch, badly oriented PV arrays and high module temperatures.

Despite good results, which have been obtained by many of the new grid-connected systems, the investigations of the operational behaviour of the reported PV systems has identified further potential for optimization. Average annual PR values of higher 0.75 are to be achieved for well-planned PV systems.

For the new systems of lower performance, the same problems as for the early installations were found and the same recommendations have to be given [6]. For BIPV, it is a challenge to combine building requirements, architectural design criteria and highest technical performance. There is a lack of long-term experiences in reliabilities of PV systems due to missing monitoring programmes. For a wider dissemination of PV in future, monitoring activities are essential to improve quality management and reliability of PV systems.

6. REFERENCES

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