IEA INTERNATIONAL ENERGY AGENCY

Reliability Study of Grid Connected PV Systems

Field Experience and Recommended Design Practice

Task 7

Report IEA-PVPS T7-08: 2002

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PVPS

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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Responsibility for the content of this report is fully born by the Author.

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Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its 23 member countries. The European Commission also participates in the work of the Agency.

The IEA Photovoltaic Power Systems (PVPS) Programme is one of the collaborative R & D agreements established within the IEA. Since 1993, a variety of joint projects have been conducted in the applications of photovoltaic conversion of solar energy into electricity.
The Programme, whose mission is “to enhance the international collaboration efforts through which photovoltaic solar energy becomes a significant renewable energy source in the near future”, is divided into nine Tasks which address specific aspects of photovoltaic technology development and implementation. Further details about the Programme are available on the PVPS website www.iea-pvps.org.
Participating members are: Australia (AUS), Austria (AUT), Canada (CAN), Denmark (DNK), Finland (FIN), France (FRA), Germany (DEU), Israel (ISR), Italy (ITA), Japan (JPN), Korea (KOR), Mexico (MEX), The Netherlands (NLD), Norway (NOR), Portugal (PRT), Spain (ESP), Sweden (SWE), Switzerland (CHE), the United Kingdom (GBR), the United States of America (USA), as well as the European Commission.

This report presents the results of »activity« 2.7 »reliability« of Task 7 »Photovoltaics in the Built Environment«. Task 7 aims to enhance the architectural quality, the technical quality and the economic viability of photovoltaic power systems in the built environment and to assess and remove non-technical barriers for their introduction as an energy-significant option.

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AUS, AUT, CAN, CHE, DEU, NLD, ESP, SWE, GBR and USA collaborated in this activity.

The report expresses, as nearly as possible, an international consensus of the opinions on the subjects dealt with.

Executive Summary

In the frame of IEA PVPS Task 7 »PV in the Built Environment« a survey was conducted to collect information on faults, failures and poor performance from PV plants. Data were collected from Australian, Austrian, British, Canadian, Dutch, German, Japanese, Spanish, Swedish, Swiss and US systems. The focus lies on residential systems with a nominal power of 1 – 5 kWp, but large systems up to the 3.3 MWp "Serre" plant were included as well.

Looking at failures statistics over time from residential PV programs shows the typical "learning curve" of decreasing failure rates. The inverter still proves to be the weakest component.
Standard PV modules have reached a high quality standard today. They have matured over the last 20 years and show failure rates down to 0.01 % per year. However, there are some brands which exhibit less STC power than stated by the manufacturer.
Inverters too, have matured remarkably. Experience from most recent projects shows troublefree operation for 10 years. Nevertheless, when a high buy-back rate has been contracted, then care should be given for a good service of the inverter manufacturer, for example a 24 h replacement warranty.
Critical are novel electronic components, e.g. inverters, special grid interfaces or ac/dc RCDs. These need some field experience before they work reliably.

Main reasons for low yield of some systems within the German »1000-Roofs-Programme« systems were inverter failures, over-rated power of modules, partial shading of the array, soiling, and faulty connections on the dc side.

Failure analysis leads to recommendations for good design and installation practice and improved junction boxes. Modern Class II components offer the system designer the liberty to dismiss string diodes and string fuses. This results in simpler and more reliable systems.

As a minimum level of maintenance it is recommended:

- To inspect arrays once per year
- To clean arrays regularly, if soiling is noticed.
- perform a monthly check of electrical production

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1 SCOPE AND OBJECTIVE

During the last 10 years Photovoltaics have seen an impressive growth in the number of fielded systems. However, the more systems are built the more difficult it gets to keep an overview and to learn from the field experience. Knowledge of system performance rests with the many small installing companies, faults and errors are rather kept confidential.
In order to evaluate these experiences Task 7 - »Photovoltaic in the Built Environment« of the IEA´s »Photovoltaic Power Systems Programme« specifically addresses the reliability of PV systems.

The report identifies major factors influencing system reliability and provides recommendations for sound design.

2 INTRODUCTION

The main approach was to gather experience from operators of PV plants and to evaluate information from PV programs provided by the participating countries. Emphasis was placed on electrical integrity of components and system energy performance.
First, the databases used are presented, i.e. the sources of information and their limitations. Based on the comparative information, results on faults and failures are listed according to the project phases:

- planning and design
- installation and
- operation

Thus, a system designer can utilise the report in that phase, when he/she has the most influence on the future system's performance, for a sound and efficient design of a system.

One section deals with component specific experience.
Based on the reported experiences improvements for simpler and thus more reliable systems are suggested. The recommendations are backed by a standard, which is under development at IEC and to be published in 2002.

A word of prudence:
Many building integrated PV projects are built to demonstrate innovative applications for PV. They intentionally use new materials and system approaches. The use of innovative materials, such as new module types, or new mounting systems, generally will increase the risk of component failures. These projects are evaluated for lessons learned rather than to derive conclusions on the general reliability of PV components.

3 DATA BASE

Experience with PV systems is mostly anecdotal. Only in few cases statistically meaningful data are available. Among these are the German »1000-Roofs-Programme« and the Japanese »Subsidy Program for Residential PV systems«. Therefore their main features are presented in an overview. Since detailed data are available from several Swiss residential and medium sized commercial system it is included in this evaluation (Rasmussen et al. 1999, Ruoss 2000). Information on recent PV systems was provided in an updated survey by member countries of PVPS Task 7.

The number of PV systems and the quality and depth of available data varied a lot from country to country. It was therefore decided not to run a common evaluation over the reports. Instead, each data source is treated separately for analysis and then the findings are summarised.

Data from the large plants allow to assess the behaviour of different types of modules, whereas data from the residential programs allow to evaluate besides the components also the installation practice.

3.1 The German »1000-Roofs-Programme«

The German »1000-Roofs-Programme« comprised approximately 2100 PV systems built from 1991 to 1995 in Germany. They all were installed on the roofs of private residences. The programme was extensively monitored: all system owners had to provide monthly yield data and logbook reports. Furthermore, about 100 systems were monitored in detail using remote data acquisition systems at a sampling rate of 5 min. After some years a special investigation was conducted to analyse systems which showed a poor performance. An inspection of some 200 systems gained experience on the long-term hardware behaviour. The scientific work was carried out in joint co-operation by Fraunhofer ISE, FZ Rossendorf, ISFH Emmerthal, IST Energietechnik Augsburg, JRC Ispra (Italy), TÜV Rheinland, Umweltinstitut Leipzig and WIP (Becker et al., 1997, Erge et al., 1998 and Hoffmann et al., 1998).

Systems in the »1000-Roofs-Programme« were installed between 1990 and 1995. Most of the installations, 70 %, took place in 1992 and 1993. The total installed power was 5.3 MWp, average nominal power was 2.6 kWp, typical power values were 1.6 kWp, 1.9 kWp, 3.2 kWp and 4.8 kWp. This distribution was caused by the power rating of available inverters.

3.2 The Japanese Subsidy Program for Residential PV

In Japan some 70 000 PV systems have been installed on residential houses, commercial buildings, etc. under national subsidy programs. The “New Energy Foundation” (NEF) has investigated troubles of residential PV systems. NEF investigated troubles with simple questionnaire every year. There is no detailed information requested in the questionnaire for keeping owner’s privacy.

Reports from some 2200 (for 1998) residential systems were evaluated.

An overview on Japanese PV Programmes is given in (Kurokawa 2001).

3.3 Survey of “Upper Austria”

The utility of “Upper Austria” (Energie AG Oberösterreich) conducted a survey among all owners of PV systems in their area. The responses covered about 95 systems with a total operation time of 4 267 months. Average system size was calculated at 2.7 kWp.
Most of the systems were commissioned in 1996 and 1997, however, some systems date back until 1990.

3.4 The German »Sonne in der Schule« (Sun at School) Programme

»Sonne in der Schule« is a government programme to sponsor PV systems of approximately 1 kWp power for schools and use them for educational purpose. Module and inverter type can be freely chosen. Information on electricity production and irregular events are collected quarterly from the schools and evaluated in annual reports (Hoffmann 1999 and 2000). The quality of information depends on the responsible group at the specific school. However, we believe that information gained from the schools fairly well represents the perception of a typical owner of a residential PV system, who is not an expert on PV and simple tries to get a rough clue, if anything unusual happens.
By end 2000 some 330 schools participated in the programme. Programme evaluation relies on information given by the school representatives. Around 200 schools submitted useful performance data.

3.5 Task 7 Survey

In April 2001 Task 7 conducted a second query on reliability data from PV systems. This survey not only asked for incidents, but also for systems, which have been working well ever since commissioning. It was the intention of the survey to identify module and inverter types, which proved to work well.
Quantitative responses to the questionnaire (April 2001) were received from Germany, Sweden, Switzerland and United Kingdom, comments also from PVPS Task 2.
Data covered a German programme called “Sonne in der Schule”.
For evaluation these data are treated differently from the reminder of this section, because they provide annual data like those from the German and Japanese roof-top programs. Furthermore, the information on incidents is collected in a very similar way as in the large programmes from lay persons. Therefore, we believe that these data can fairly well be compared to each other.

In contrast, the other data were provided by system operators or installers, who accompanied their systems over time. Information is therefore assumed to be quite accurate.

Switzerland data cover mostly the demosite pavilions at the EPFL (Technical University) Lausanne. Some 14 pavilions are equipped with various PV

systems demonstrating different manufacturers building integration approaches. Their size is between 0.8 and 2.5 kWp. Also some larger installations are included.
In total 157 years of inverter operation are reported.

Swedish data covered some 4 systems with a total power of 63 kWp. Experience with one system reaches back until 1984.

Data from UK cover installations of about 90 kWp employing some 75 inverters, which were commissioned between February 1999 and May 2001. Data were provided by the company, which had erected all the systems.

3.6 Large PV Plants

Another source of statistically meaningful data are large plants with thousands of modules. A survey was conducted asking owners of large plants, e.g. RWE Energie, Solarwasserstoff Bayern, ENEL, to share their operational experience of faults and failures affecting the electrical circuits. 13 reports were evaluated including some on large plants as Kobern-Gondorf (Germany), Neurather See (Germany), Neunburg vorm Wald (Laukamp H. et al., 1999). The complete report is attached in appendix 1.

Further information was provided on the Swiss plant »Mount Soleil« (Kälin 2000).

In this section also the Swiss »Solar stock exchange« of the »ewz« (Elektrizitätswerk der Stadt Zürich, local utility of the city of Zurich) is reported. This program comprises 42 installations from 6 kWp to 100 kWp with a total capacity of 1.6 MWp. A careful performance evaluation was done after some 1-5 years of operation (Ruoss 2000).

4 FAULTS AND FAILURES

4.1 Fault Statistics of Large Residential PV Programs

In the large residential PV Programs in Germany and Japan owners of PV systems had /have to regularly report on the operation of their systems. Specifically, information on system failures is seeked for. The information thus collected is usually not technically deep, but it reflects the perception of the owners.
Due to the similar method of gathering performance data the program »Sonne in der Schule« is included at this section, though the information had been collected under the task 7 survey.

Figures 1 to 3 show results of the queries. Type of failure and failure frequency per 100 systems are presented. Results in figures 1 and 2 are biased insofar as systems with “no response to questionnaire “ were counted as “no trouble”.
The failure rate decreased by approx. 5.5 % per year in Germany and by about 4 % in Japan.

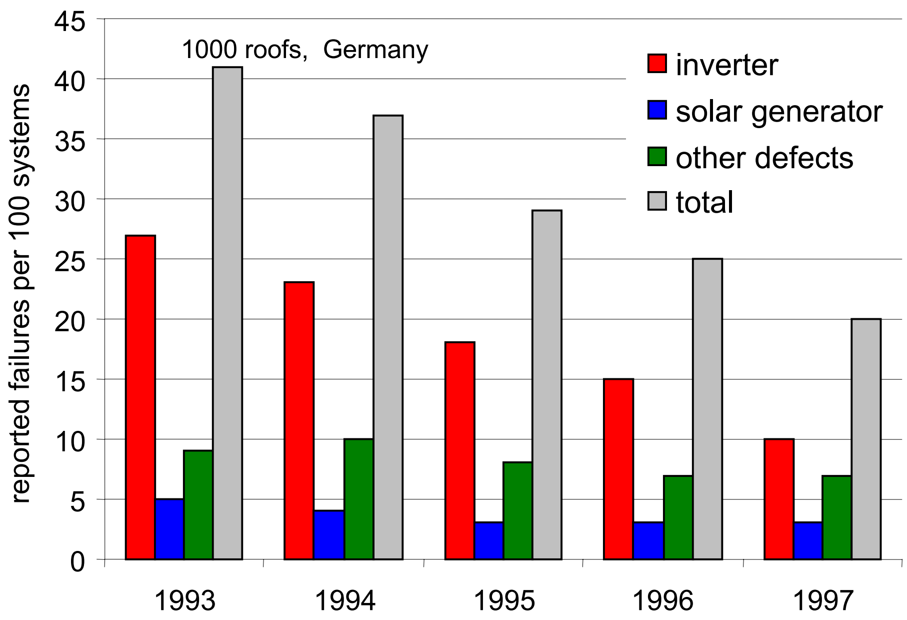

Fig: 1: Failures by main component as reported by the system owners under the »1000-Roofs-Programme« (Erge et al. 1998).

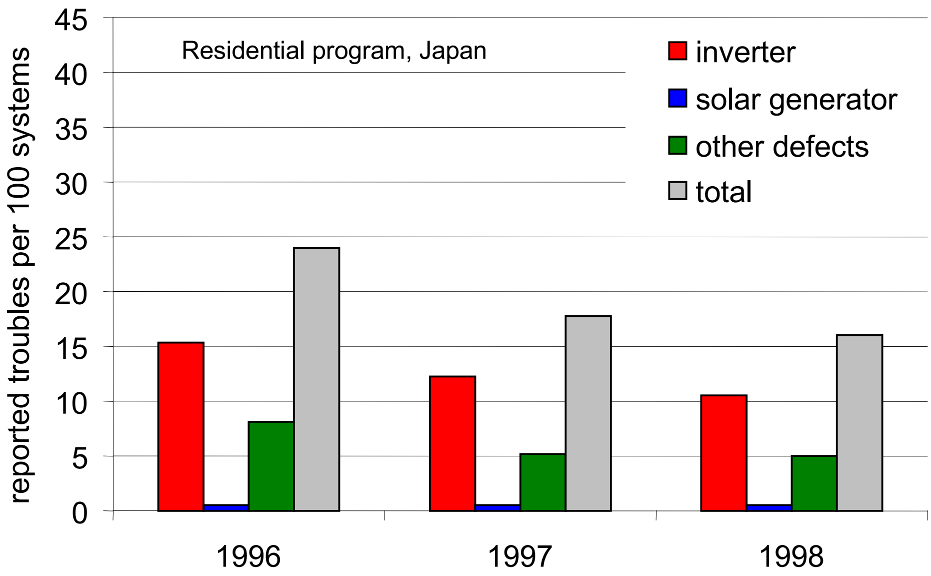

Fig: 2: Failures by main component as reported by the system owners under the »Subsidy Program for Residential PV systems « (Nishikawa 2000).

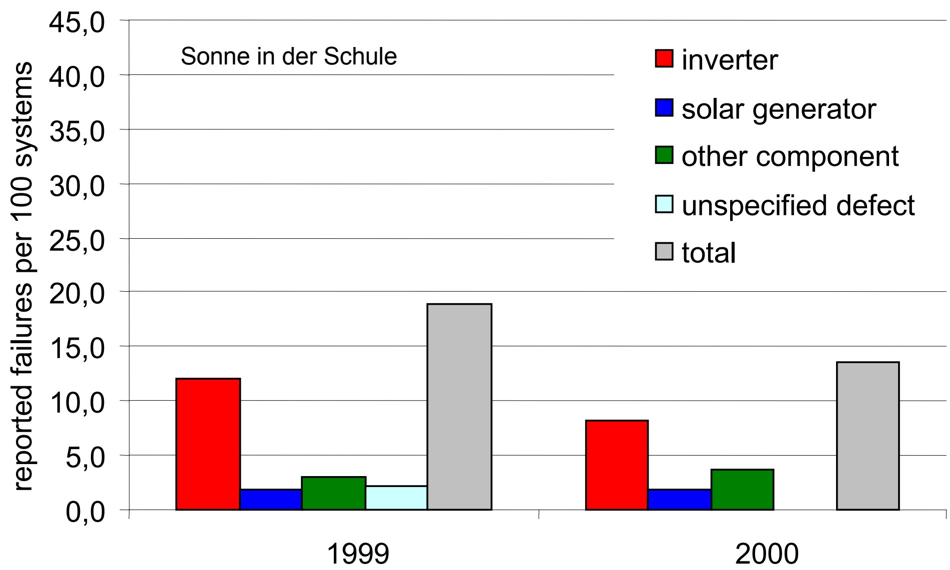

Fig.3: Reported troubles and failures per 100 systems from »Sonne in der Schule« (Hoffmann 1999 and 2000).

The information given from owners does not always distinguish between a temporary malfunction, (which automatically resets) and a failure, i.e. a defect requiring a repair. Even less a malfunction can be distinguished from an inverter shut down due to irregular grid conditions. Data for figure 3 include all such effects. Considering true hardware reliability of the inverter, these data are conservative.

In all reports the inverter was by far the most troublesome component. It accounts for about 66 % of reported troubles. However, it is obvious that the number of troubles decreases continuously over time. Reports from recently installed system show a significant lower failure rate for inverters (compare figure 1 and 3).
We assume this to be a result of a maturing in technology.
Inverters benefited from advances in semiconductor industry. Components became more reliable and system installers became more and more experienced in their practices. Above all, higher numbers of installations helped to standardise the systems and their installation.

More data on module and inverter failures is presented in section 5.

4.2 Planning and Design Faults

Reliability begins before the first hardware is installed. A good planning and design can boost the system performance as well as poor components can compromise it. This is illustrated by »specific yield« data from The Netherlands and the »1000-Roofs-Programme«.

4.2.1 Development of specific yield

Figure 4 below shows the yield of a number of systems monitored in the Netherlands in the period 1992 – 1997. The systems have varying tilt angle and orientation, although most of them are optimised quite well in this aspect. None of the systems is subjected to significant shading. All systems are based on crystalline silicon technology-modules. Inverter outage times are compensated for.

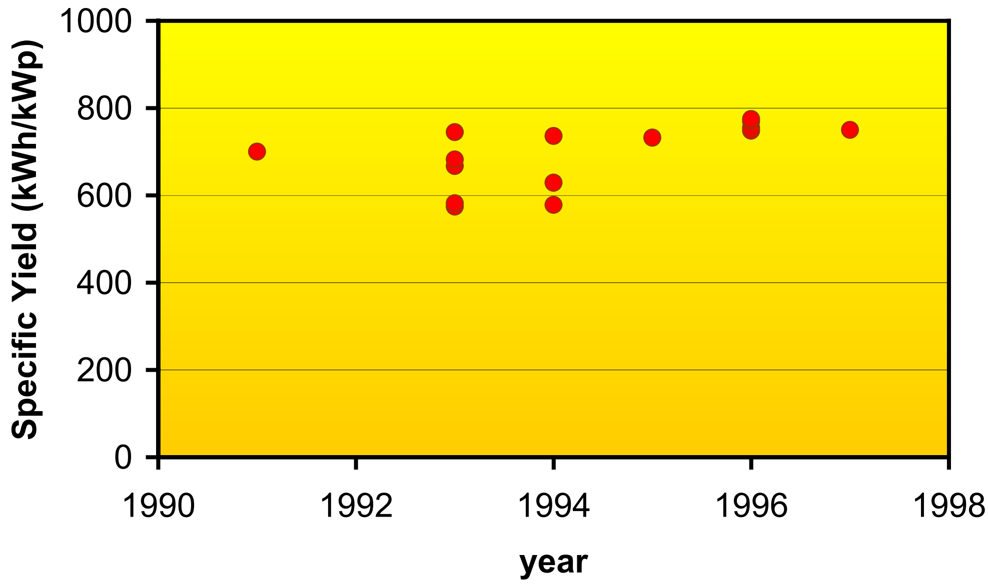

Fig. 4: Specific yield of Dutch PV systems over the year of commissioning.

From the figure, a few things can be learned:

- Judging from the upper values per year, the maximum achievable performance of the systems has been fairly constant over time.
- Systems built in recent years show a higher performance than those from earlier years.

We assume this improvement is related to learning effects of system designers.

4.2.2 Low yield analysis in the »1000-Roofs-Programme«

Looking at the annual yield of the systems shows an astonishing broad distribution (figure 5). This cannot be explained by the slightly uneven irradiation over Germany.
To understand the phenomenon a special investigation was conducted. It revealed that a significant fraction of the poor performance was caused by prolonged inverter failures. Accounting for these systems still left some 100 systems with too low yield. Nearly all of these systems were inspected and 17 were analysed in detail (Hoffmann V.U. et al., 1998, Erge Th., et al., 1998).
Four main reasons for poor performance were identified :

- inverter failures
- real power of a module below its name plate power
- partial shading of the generator by trees, other buildings and protruding building parts
- defects in the dc installation causing interrupted strings

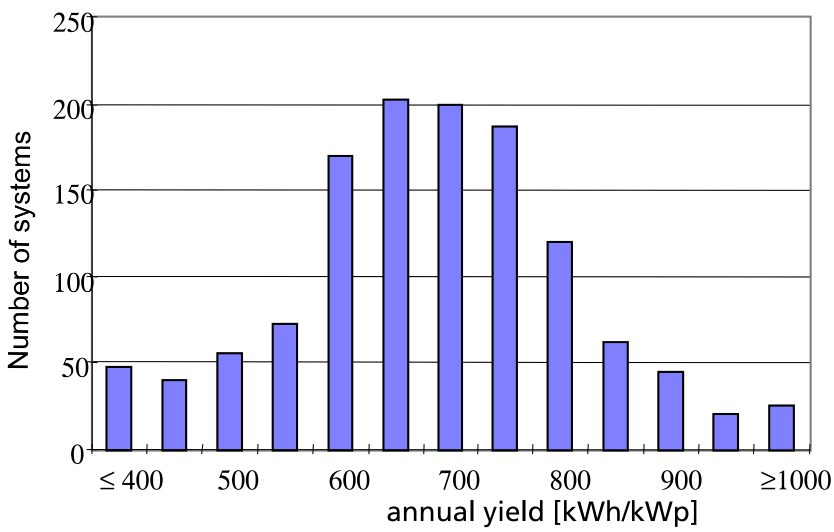

Fig. 5: Distribution of annual specific yield in 1996 (data from 1243 PV systems).

The inverter failures were mostly attributed to an immature state-of-the-art and they excluded from the low-yield analysis. The other effects were assessed with respect to their impact on annual energy yield (table I).

Table I: annual energy losses for 17 low yield systems

Fault type	**peak loss in %**	**average loss in %**
Module over rating	>20	ca. 10
Partial shading by nearby trees	25	ca. 10
String interruptions	>20	15

The determination of generator power at STC frequently revealed power deficits of 10 % to 20 % compared with the datasheet values given by the module manufacturers. Nominal STC power was reached only by two module manufacturers: Siemens and GPV (Hoffmann et al., 1998), see figure 6.

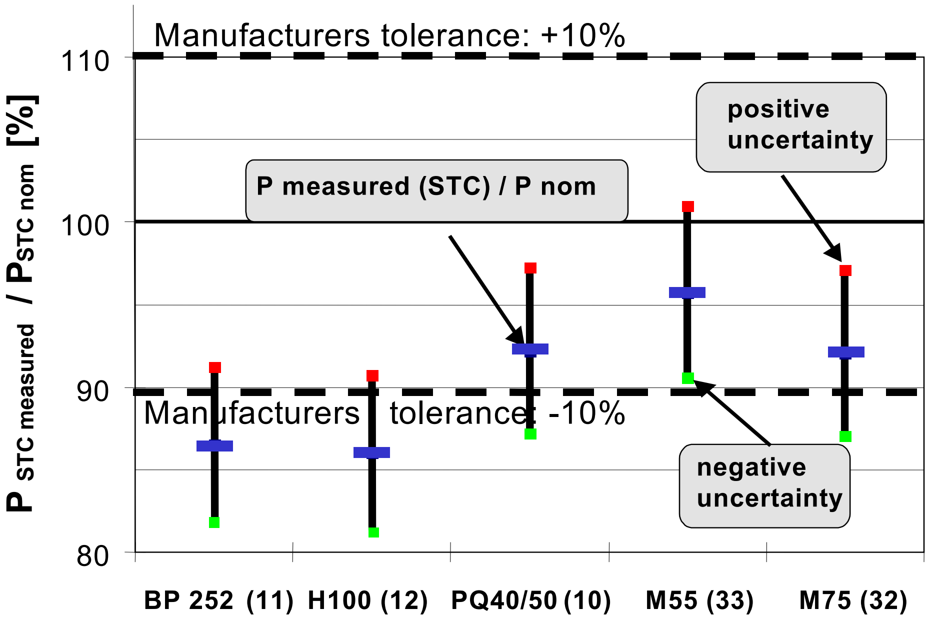

Fig. 6: Some manufacturers power ratings cannot be confirmed in field operation .

After some five years of operation 200 selected PV systems were inspected by the end of 1997. Table II shows which design flaws were noticed.

Table II: PV system defects and deficiencies found by inspections of 200 »1000-Roofs-Programme« systems

planning and design problems	**systems affected**
(partial) shading of the PV generator	41 %
unsuitable string fuses or overvoltage protection devices	15 %
unsuitable isolation switches between PV array and inverter	56 %

The number of sites affected by partial shading is amazingly high. To be fair it must be noted that a system installer runs a business and wants to satisfy his client, even if the site is not optimally suited. Home owners sometimes order a PV system regardless of shading problems.

4.2.3 System design flaws

Rasmussen et al. (1999) report an interesting interaction of degradation or wrong manufacturer's data of modules, poor inverter behaviour and system design. An eleven years old system consisting of several strings of six modules ARCO M55 in series was retrofitted with a new inverter. The modules showed poor I-V curves compared to the data sheet (fig. 7).

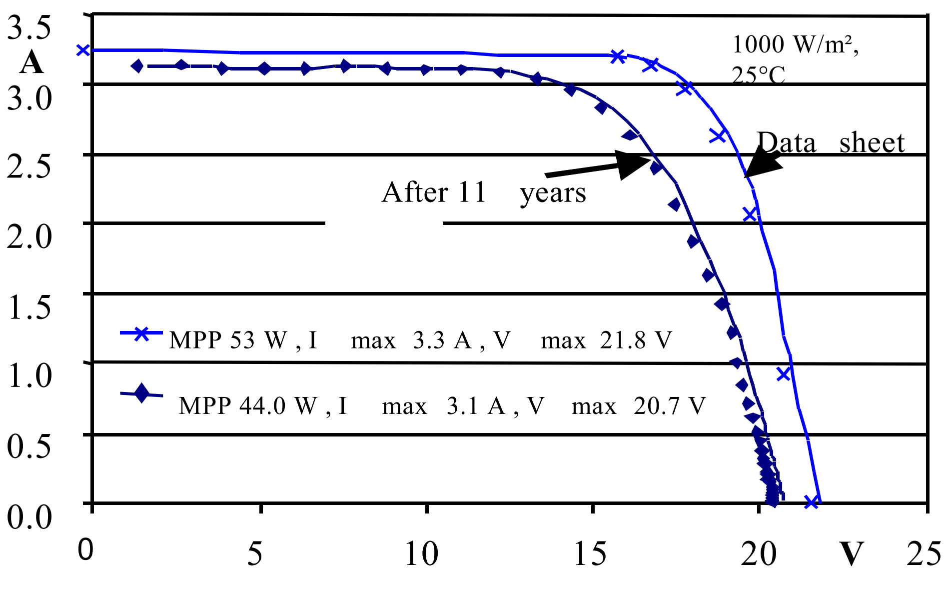

Fig. 7: I-V curve of a module after 11 years (Rasmussen et al. (1999))

When the system was started with the new inverter, a power drop at higher irradiance levels was noted. The analysis revealed that the inverter did not reach its specified minimum MPP input voltage of 72 V, but limited the input voltage at 85 V. Thus the inverter was not able to track the MPP under the conditions of elevated module temperature and degraded V_{oc}.
Conclusion: System designers should allow for a margin between

operational V_{MPP} and Minimum input voltage of the inverter to account for such combined effects and be assured of the exact and right value from the inverter data sheet.

Like most reports the »ewz« report (Ruoss 2000) noted inverter problems as a major cause for energy losses.
An important lesson learned concerns the planning and operation strategy of the systems: the main coupling switch (if any) to the grid shall be operated automatically!
Originally, the »ewz« utility required an coupling switch to be operated manually. After a tripping they wanted somebody to check the system and to acknowledge the incident on site. However, most systems operate unattended and some tripping stayed unnoticed for a week. This caused energy losses. As a consequence the requirement for a manual reset was abandoned and large systems are now coupled through an automatic switch. Furthermore the set points for the monitoring relays were adjusted to accommodate the local noise levels to reduce the frequency of nuisance tripping.
Since these change had been implemented no problems from coupling switches had been reported.

In Japan the “Japan Quality Assurance Organisation” (JQA) has investigated troubles of PV system in detail by a contract with NEDO. Reports from residential systems identified several causes for troubles, which occurred in multiple systems (Nishikawa 2000):

- Power limitation by inverter to keep upper limit for line voltage
- Partial shading in PV awnings by upper rows
- PV generator operating voltage below inverter input window
- Power loss due to undersized inverter

The first of these troubles should preferably be solved by reducing the set voltage of the distribution network and thus allowing a larger margin between operational grid voltage and upper limit of grid voltage. Alternatively, inverters` outputs have to be reduced.
All other troubles result from poor design or externally enforced late changes in system design.

4.2.4 Hot-Spots in Large Area Modules

Bypass diodes for hot-spot protection of large area modules are sometimes left out. Protection from hot-spots is totally ignored or seeked by other means, for example by using several parallel cell strings within a module (Laukamp H. et al. 1994).
Experience shows that this is a risky path. Paralleling several cell strings within a module does not protect the modules, if partial shading from nearby objects occurs regularly.

A field experiment using the shadow of an open window demonstrated the occurrence of hot-spots (Laukamp H. et al. 1998), see figure 8 for the situation.

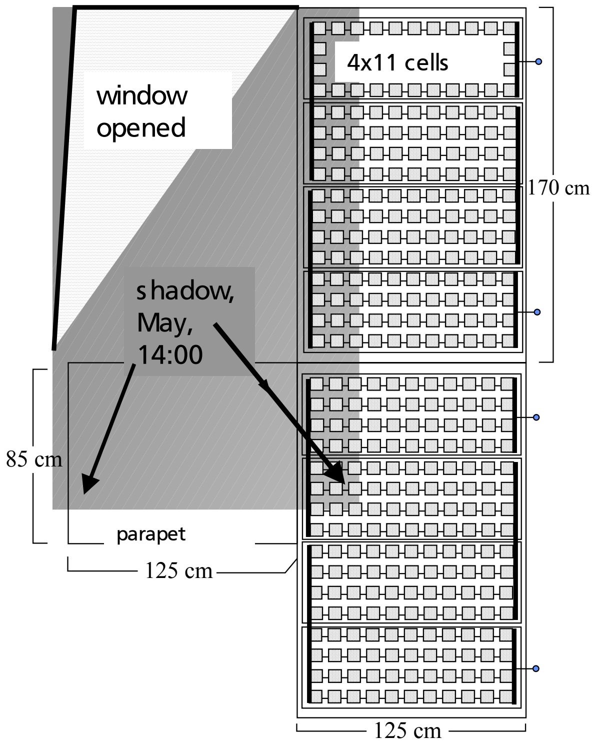

Fig. 8: An open window casts its shade on the adjacent modules. Modules are constructed from submodules using 11x 4 cells. String wiring is horizontal.

An infrared image clearly shows local heating of the modules – the beginning of a hot-spot (fig. 9). The maximum surface temperature measured during the experiment was 98 °C. Though no module damage was visible after the experiment, a year later we found several modules with cell and glass damage from hot-spots. These modules were shaded by a street lamp in the winter.

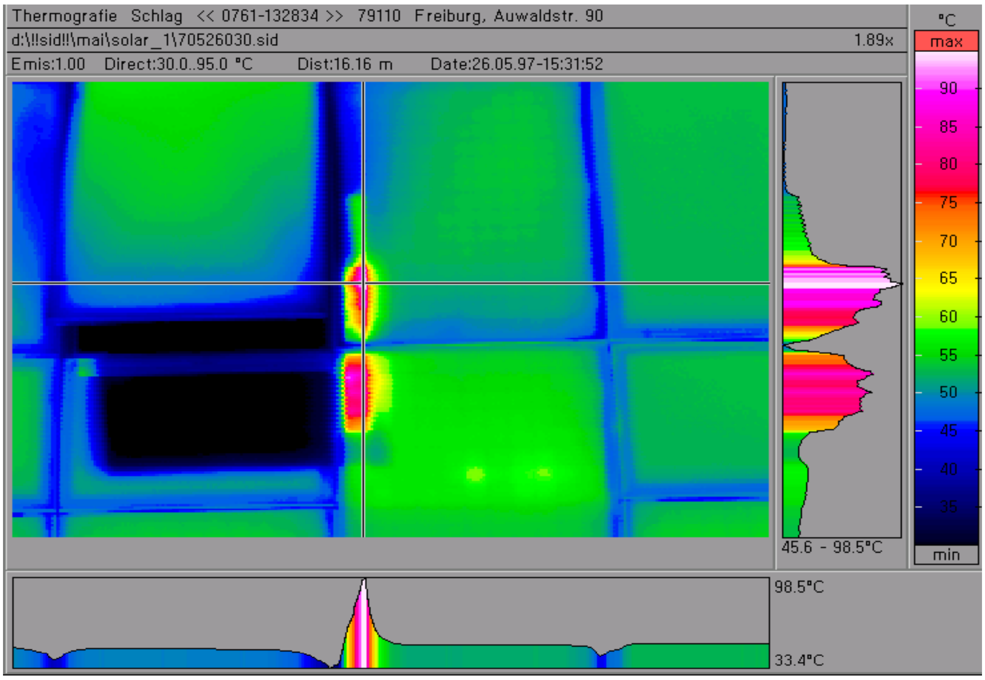

Fig. 9: Infrared image of the situation from figure 8. On the left side the open window is visible. The glass facade section shaded by the window appears dark, i.e. cool. Two modules in the centre of the image are partially shaded. They show local high temperatures up to 98 °C. The cross lines mark the cuts for the temperature distributions shown at the bottom and the right side of the image.

4.3 Installation Faults

Many installation faults of different severity were found in the 200 systems from the »1000-Roofs-Programme«, which were inspected.
Table III gives an overview on the type of defect and the relative occurrence.

Table III: type and frequency of installation defect

installation faults	**fraction of systems affected**
solar generator cabling not mechanically fastened	24 %
lack of heat dissipation of string diodes	60 %
loose terminal connections	5 %
unsealed cable entry from top of junction box	-
broken printed circuit boards (PCB) in junction box	-

Loose or broken connections can be caused by poor workmanship during installation. However, these defects can also be caused by thermal cycling, which works the screwed connections loose with time. Sometimes terminals were found corroded after only 2 years (figure 10). Presumably, condensing moisture could not drain and accumulated in the junction box (j-box).

In a few cases broken printed circuit boards (PCB) in junction boxes were reported, which caused arcing across the fissures. Possibly, the cracks were caused by too much torque or pressure.
Depending mainly on the operating voltage, these faults can lead to an electric arc and subsequently to destruction of the module junction box.

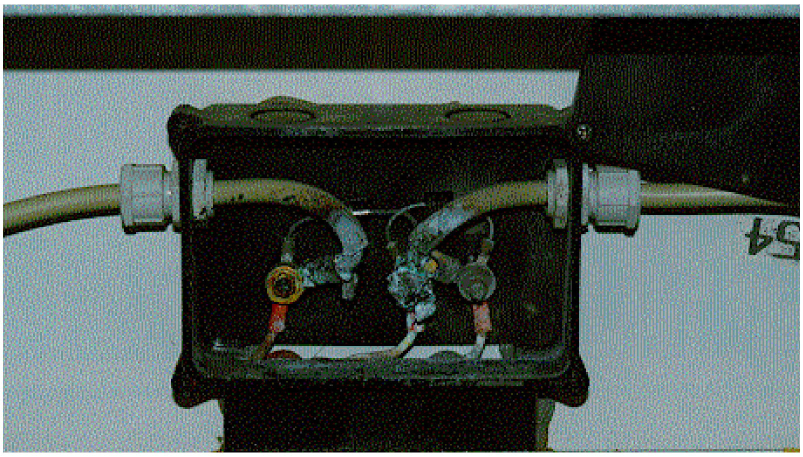

Fig. 10: Corroded contacts probably due to lack of water drainage. This connection will not last 20 years (Laukamp, Häberlin et. al.)

4.4 Operational Faults

»Operational faults« are faults which originate from the operation of a system. Faults, which result from component weakness, or improper planning or installation are excluded. Table IV gives an overview on operational troubles found in the »1000-Roofs-Programme«

Table IV: defects and deficiencies found by inspections of 200 »1000-Roofs-Programme« PV systems

problems during operation	**fraction of systems affected**
corrosion and defects in mounting structure	19 %
moderate to strong soiling of modules	12 %
defect string fuses	4 %
faulty modules (broken glass, open circuits, discoloration)	< 2 %
defect string diodes	< 2 %
corroded plug/receptacle connectors	1 %
defect overvoltage protection devices	< 1 %

4.4.1 Soiling

The impact of soiling is strongly site dependent. PV Modules on the roof of the former Fraunhofer ISE building showed virtually no soiling after 10 years of operation, only very little growth of lichen (Figure 11).

Fig. 11: Modules at Fraunhofer ISE after 11 years of operation.

Soiling affected some 10 % of the »1000-Roofs« systems. The average effect on energy production was fairly small, below 2 %.
However, depending on the mounting some module types are more prone energy losses from soiling. PV modules mounted with less than 30 ° inclination and high horizontal frame or cover profiles were found to loose 2-6 % of annual energy. The worst soiled string delivered 18 % more power after cleaning.

Soiling appeared also in other systems as an important cause for loss of energy (Häberlin 1998).

Some very illustrative pictures are presented from Switzerland (Ruoss 2000), from systems which operate in the »Solar stock exchange« of the »ewz« at Zurich.
The study concludes that rain provides a good degree of cleaning. Dust, pollen and the like are washed away. However, sticky dirt like bird droppings may stay even during severe rainstorms (Fig. 12).
The most critical part of a module is the lower edge. Especially with rather low inclinations, soiling at the edge of the frame occurs. By often repeated water collection in the shallow puddle between frame and glass and consecutive evaporation dirt accumulates (Fig 13). Once it causes shading of the cells, this dirt reduces the available power from a module. Densely packed modules with little distance between cells and frame are especially concerned. Laminates allow free run-off of the water. Therefore, they are less prone to this effect (Fig. 14).

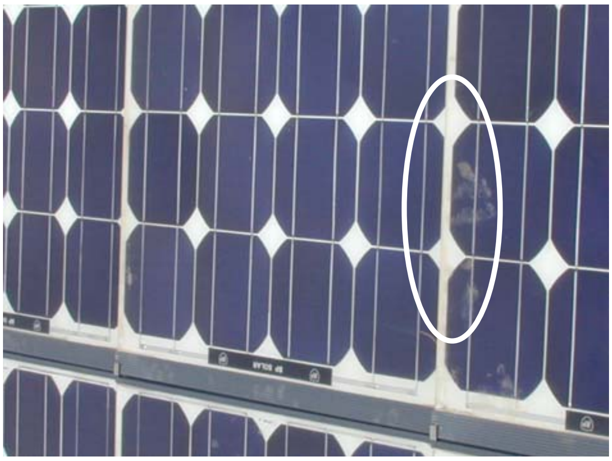

Fig. 12: Some dirt stays after a heavy rainfall (ewz)

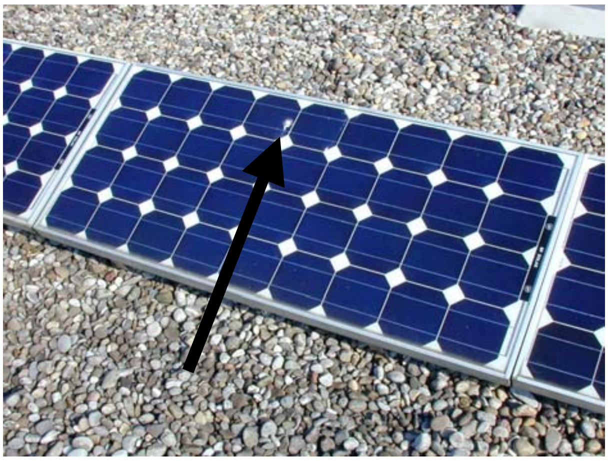

Fig. 13: Bird dropping stays after a heavy rainfall (ewz)

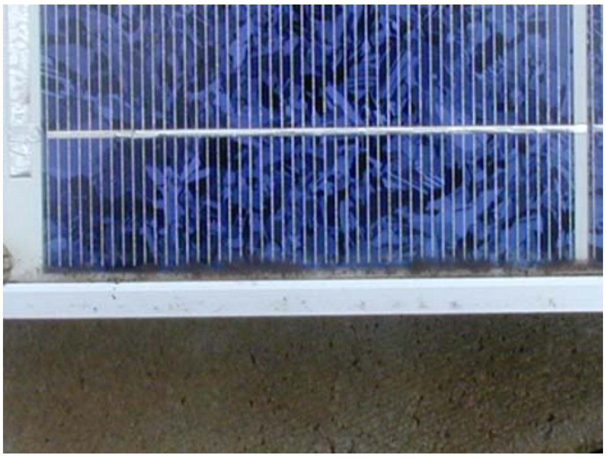

Fig. 14: Dirt accumulation above the frame (ewz).

Fig. 15 This laminate is free of dirt (ewz).

Over time dirt accumulation may collect enough soil to allow plant growth (Fig. 16). This effect can be resolved only by yearly manual cleaning, by using laminates or by using a new development – a ¾ frame (Fig. 17).

Fig. 16 Tree years after instalation moss has grown.(ewz).

Fig. 17: SOLRIF® module with a 3/4 frame (ewz).

3/4 frame means that at the lower edge, only the rear part of the frame is mounted and the front part is omitted. Thus, the module is protected by a frame and simultaneously water can drain freely. Currently, one such system is available –called SOLRIF®. It is designed for integration into sloped roofs. These modules can be mounted the same way as conventional roof tiles.

Generally, soiling is a reversible effect. However, there are some situations, where corrosive or sticky dirt is very hard to remove. One example is exhaust fumes from a heating system (ewz). Acidic and sulphuric fumes create a dirt layer, which reportedly is very difficult to remove (Fig. 18 and 19).

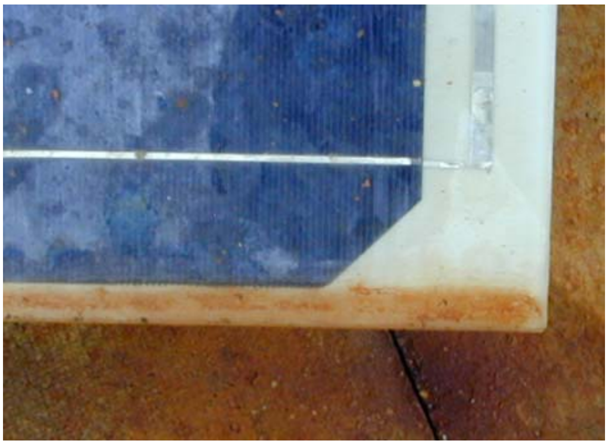

Fig. 18: Dirt from exhaust fumes (ewz).

Fig. 19: Detail of a module edge close to a chimney.

Similar effects have been reported near a railway station (Häberlin 1998). Here, a special pollution from braking dust seems to create a good situation for pioneer plants like lichen. These then enable larger plants to settle down. Over some 5 years a nearly continuos decline in specific yield was noted. Cleaning eventually lead to some 10 % increase in Maximum power P_{mpp}.

Häberlin recommends a regular annual cleaning.

4.4.2 Lightning strikes

Data on system damage due to lighting strikes were mostly not reported from the responding countries. However, the „Upper Austrian“ query asked for inverter damage which occurred during thunderstorms.
They found a chance of inverter damage from nearby lightning strike of once in 40 years.

4.4.3 Extreme environments

Extreme environments are considered to include arctic and alpine locations as well as heavy storms.
In winter 1999 a heavy storm called “Lothar” caused a lot of damage in central Europe. It also affected some PV systems.
In Switzerland part of a roof installation was overthrown destroying 3 modules. The reason is assumed to be an insufficient stability of the mounting construction at the location close to the buildings rim, where high turbulence is to be expected.
Also from “ Sonne in der Schule “ two damages are reported without further details. These arrays employed weight foundations.

From alpine sites specific failures are reported, which are not encountered anywhere else (Wilk 1999).
These include damage from grains of rock blown by strong winds onto the modules. This caused impressions on the glass, but did not affect the module output.
Piling up of snow and ice occasionally did cause glass breakage. Additional reinforcement of the module frames solved these problems.

5 COMPONENTS

5.1 Modules

5.1.1 Standard Modules

Standard modules have proven to reach remarkable lifetimes. Figure 20 shows module power measurements taken over 22 years at the Swedish test site Sandkullen (Andersson, Hedstrom (2000)). The modules had been installed in 1977.

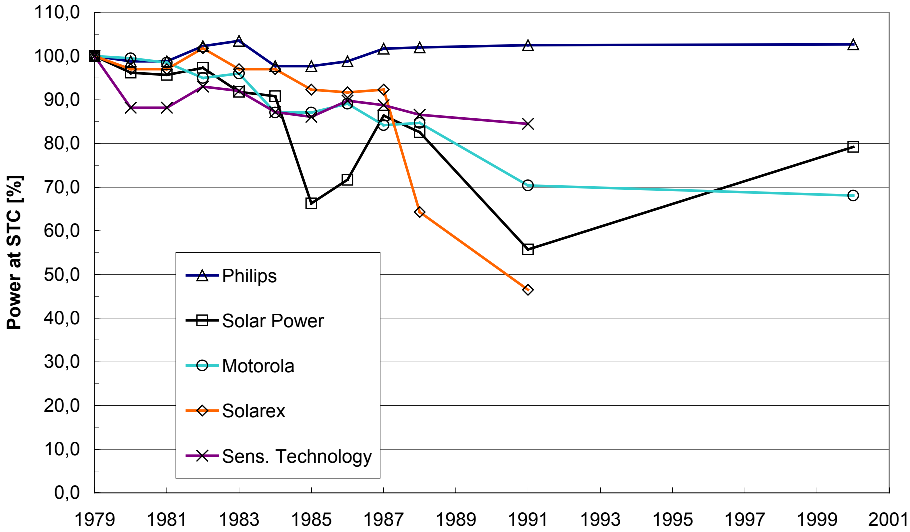

Fig 20: Relative power at STC referred to initial power. Long-term measurements at he Swedish test site Sandkullen show that a good module performs without detectable power degradation over 21 years.

Visual inspection of the „Phillips" module shows its integrity (figure 21).

Field experience from more recent projects confirm this conclusion (figure 22).

Fig 21: The „Phillips" module from Sandkullen after 22 years outdoors.

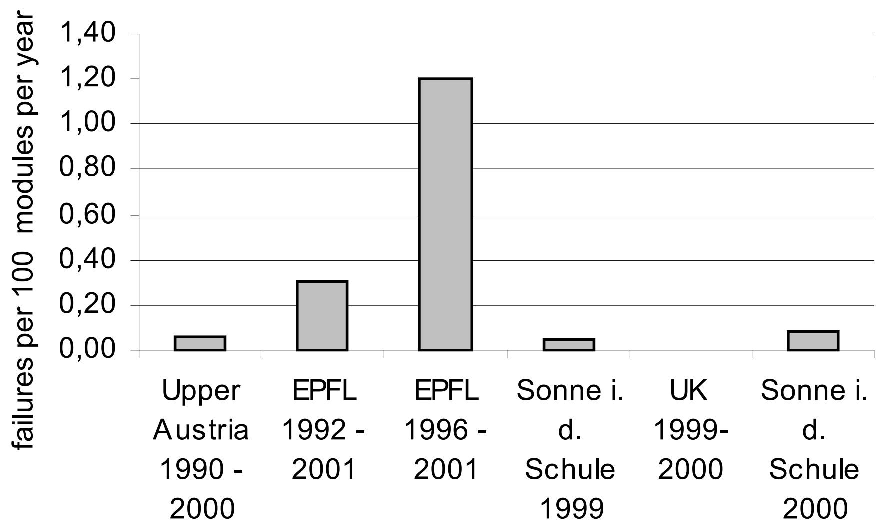

Fig. 22: Module failures and operational troubles for different task 7 survey responses normalised to 100 modules operating for one year. EPFL and UK data are based on failure information from an experienced system operator/installer, the three othert columns are based on questionnaire and monitoring information from lay persons. The high values in columns 2 and 3 result from one flawed module type. The fifth column is indeed empty. Nominal module power was normalised to 50 W.

The task 7 survey showed low module failure rates. Excluding one flawed module type, which caused the peak failure rate at EPFL, no module failures were noted at EPFL and UK. Surveys in upper Austria and »Sonne in der Schule»showed failures rates below 0.1 % per year. For this figure modules were assumed to be standard modules of 50 Wp.

Experience from large plants indicates a failure rate in the range of 1 (Mont Soleil, Kälin 2000) to 10 (Serre plant, Laukamp et al. 1999) modules out of 10000 per year. For the Mt. Soleil plant at least half of these failures are believed to result from vandalism. Thus, module durability is even better.

Among the rather few module failures reported in the „large systems“ survey the predominant location of faults were the module connection boxes (j-box). To correctly appreciate the damage one has to note that in a very large PV plant within two years some 40 j-boxes out of 40 000 were affected. Of these some 20 cases of disconnected soldered connections occurred and 12 j-boxes were damaged by arcs. However, in all cases the arc was contained in the J-box and did not cause outside damage (Laukamp et al. 1999).

We expect that failures and troubles due to PV Modules and arrays will still be reduced by two technological developments: Plug connectors yielding more reliable in-field connections and larger modules yielding a lower number of series connections per kWp installed.

5.1.2 Custom Modules

The increasing interest in building integrated photovoltaics lead to the development of new module manufacturing processes. Especially for large area modules cast resin processes for glass/glass modules were developed. These processes allow to manufacture PV modules of a size up to 6 m².

Unforeseen medium and long term effects of degradation have occurred regularly with new manufacturing processes. We have to anticipate them also for novel PV equipment production.
Many building integrated projects are built to demonstrate innovative applications for PV. They intentionally use new materials and system approaches. The use of innovative materials, such as new module types, generally will increase the risk of component failures. These projects cannot be used to derive general statement on the reliability of standard PV components.

Recently, it was reported that some cast resin modules showed signs of delamination (PHOTON 2001). The manufacturer assumes that a chemical reaction between his resin and the anti-reflective coating of the concerned cell caused this effect. Modules, reportedly, are replaced at the manufactures expense.
A similar effect had been noticed at a demosite pavilion.

As a system designer/owner one can take provisions against such mishaps by writing clear definitions into the purchase contract.
It should be stated that modules will be replaced free-of-charge by the manufacturer, when electrical or optical degradation of a percentage or area to be defined occurs in a specified time period.
If possible, this warranty should also cover the necessary labour to actually perform the replacement.

5.1.3 Amorphous thin film Modules

Thin film modules were used in only one of the reported systems (Sweden). Here, they showed a large degradation and did not perform as well as expected.

5.1.4 Locating Module disruptions

Though it can be stated that modules seldom fail, it still occurs. Especially new module types may be subject to a systematic failure mechanism, which shows after some years of operation. This has been the case with a module type, which Fraunhofer ISE used extensively on alpine huts.
After a series of module failures, which involved interruptions of the intercell connects, a method was developed to locate those defective modules on a rooftop. Furthermore, a special portable device was developed, which enables to locate such faults within a module in a non-intrusive way (Schmidt 1996).
The device is available through Fraunhofer ISE.

5.2 Inverters

A theoretical analysis shows that inverter should have a “Mean Time Between Failures” (MTBF) about 50 years as long as they are not exposed to excessive temperature. (For example, mounted directly at a module without any rear side ventilation.) (Wilk 1997).

Actual experience is quite different.
As can be seen from figures 1 and 2 inverters were the most vulnerable component in PV systems. This observation was unanimously supported from all countries.
Data for figures 1 and 2 was mostly gained from older types of inverters. It is a very interesting question, if new products demonstrate improvements.

According to (Wilk 1997) from 1995 to 1996 the failure rate indeed dropped from 0.7 to 0.4 defect per inverter and year.
He believes that inverters were mostly damaged by surge voltages from the grid. Products have been improved, design errors and software glitches have been corrected.
Data from the 2001 task 7 survey are indeed encouraging:

- From the German “Sonne in der Schule” Program between 12 and 8 inverter failures per 100 inverters and year are reported for some 350 inverter-years. This relates to a mean failure rate of about 1 failure in 8 to 13 years. The reported failures include also various malfunctions, which were probably caused by improper grid conditions.

- Switzerland data from EPFL covering mostly the demosite pavilions show a distinct improvement over time from 11 to 4 failures per 100 inverter-years. This relates to a mean failure rate of about one failure in 7 years for a total of 133 inverter-years from 1992 to 2001 and one failure in 24 inverter-years for the period of 1996 to 2001.

- Data from UK cover installations, which had been commissioned between February 1999 and May 2001, of about 90 kWp array capacity employing some 140 inverters, including some 60 Module Integrated Inverters.
  So far no system failure has been noted.

Figure 23 shows inverter failure rates from the task 7 survey.
It shows an average of about 10 years between failures.

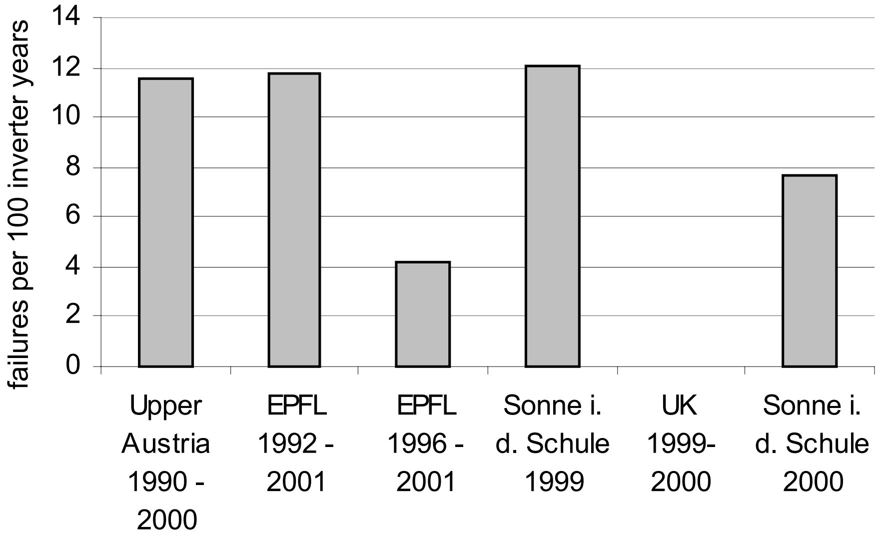

Fig. 23: Inverter failures and operational troubles for different task 7 survey responses normalised to 100 inverters operating for one year. The quoted year is that of commissioning. Only for the two »Sonne i.d. Schule« columns the quoted year indicates the reporting year. Columns 2, 3, and 5 are based on failure information from an experienced system operator/installer, the three other columns are based on questionnaire and monitoring information from lay persons. The fifth column is indeed empty.

Considering reports from experienced operators the graph indicates a clear improvement of average failure rates in recent years. Considering lay persons´ reports this conclusion is less apparent. We assume that installation flaws and troubles with the »ENS«, the German islanding protection system, in the inverters cause some of the fault reports.
The trend to lower failure rates is most likely due to reliability improvements in »younger« systems with more advanced inverters. But also older systems benefit from improved components, since unreliable inverters have been replaced by new products.

A remarkable inverter lifetime is reported from Sweden: a HELIONETICS inverter was in operation from 1984 until 2000 without any trouble. It was still functioning properly, when it eventually was replaced by a new inverter type during system renovation in 2000.

Entry of condensation water is reported for a Module Integrated Inverter (Wilk 1997). (See also section 3.3).

We hope to gain more insight into this issue from new project such as the Dutch »Nieuwland«, Amersfoort, (500 inverters) and the Australian »Olympic Village«, Sydney, (200 inverters) with a large number of identical inverters. These systems are just being monitored and evaluated.

6 SYSTEM DESIGN

As shown before, often poor contacts, wrong fuses and failing string diodes reduced the energy produced by PV systems. Omitting these components would benefit the overall system reliability. But, are not fuses and string diodes necessary to protect the generator and the surrounding property?
No, they aren't.
In many cases diodes and fuses may safely be omitted (fig. 24). This had been first appreciated in a German draft standard for residential PV systems (Laukamp and Bopp, 1996). Currently an IEC (International Electrotechnical Commission) standard is under development (IEC 60364 part 712) using the same approach (IEC, 1999). The exact requirements to be defined in this standard are under discussion. Therefore, we present the reasoning behind this approach. Publication of IEC 60364 part 712 is planned for late 2002.
An extensive introduction into the matter of electrical safety of PV systems can be found in (Laukamp and Bopp, 1996).

String diodes and fuses are not necessary, if the wires and the modules can carry the worst case fault current. The worst case current can be assumed to be 1.2 * $I_{sc,array}$, the short circuit current at STC of the whole PV generator. Critical is the temperature dependence of the cable used (fig. 25). Regular cables are rated up to 60 °C or 70 °C and reach their temperature limit in a rooftop installation. They may not at all be used in an heat insulated facade, where temperature peak above 80 °C.

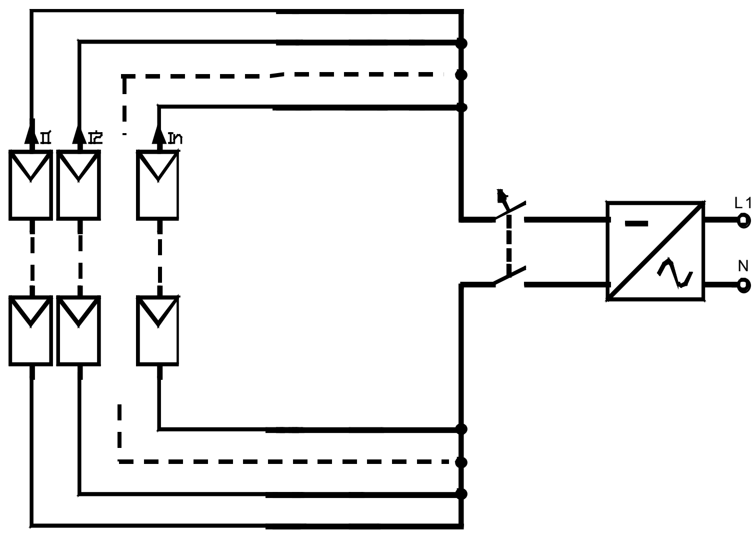

Fig. 24: Simple system design using class II[1] equipment and double insulated wires with extended temperature rating (IEC, 1999).

[1] Protection classes refer to a common classification of electrical equipment as defined in the German standard DIN VDE 0106 Teil 1. English version is IEC 64 (CO) 196.

There are cables on the market with increased temperature resistance. These offer a huge advantage with respect to permissible currents at elevated temperature. Modern cables of 2.5 mm² cross section are rated for a current capacity of several 10 A (fig. 25). These cables employ special materials for insulation, for example cross-linked polyolefines. The cable named »Radox 125« in figure 25 is just an example, cables with similar properties are available from several manufacturers.

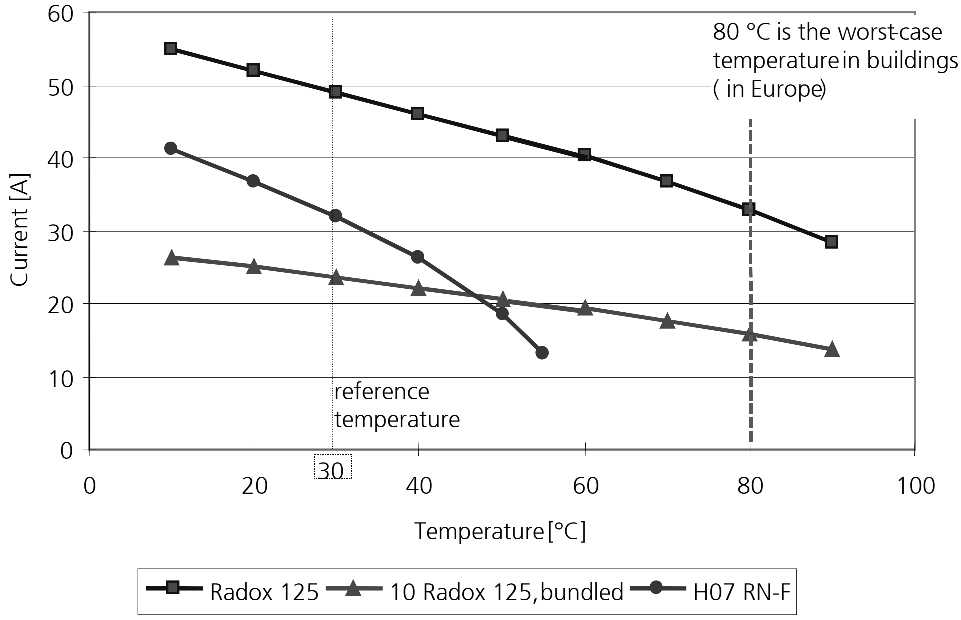

Fig. 25: Current capacity versus ambient temperature for single wires of different cable types and 10 wires of a modern, temperature improved cable type laid close together (bundling). H07 RN-F is a standard cable described in the German standard DIN VDE 0298 Teil 4. Radox 125 is a cable with improved temperature rating.
Data are taken from DIN VDE 0298 Teil 4 and manufacturers data sheets. For Radox 125 values below 30 °C were extrapolated. 30 °C is a standard reference temperature.

In smaller systems with up to 6 parallel strings of standard modules (I_n ca. 3 A), such a modern cable of 2.5 mm² cross section is sufficient to provide overload and short circuit protection, because it can carry all the generator short-circuit current. Incidentally, this is about the current which a module can carry in forward direction (Gajewski 1998).
As a precaution for long-term degradation, systems with a larger number of strings or high-current modules, should employ fuses for individual strings or groups of strings. Thus an overloading of wires is excluded, even if insulation failures occur after long-term degradation.

The exact number of strings that can be connected in parallel without necessitating protection by fuses depends on the used cable type, its cross section, the prospective maximum ambient temperature, the spatial

arrangement, as bundling of cables might cause mutual heating of wires and the cooling effect of the nearby surrounding.
If PV modules, all connection boxes and other equipment in the dc circuit and the inverter are rated for protection class II, i.e. they employ reinforced or double insulation, and if double insulated wires of high temperature rating are used, than no additional overload protection is required. This method of wiring used to be called »earth fault- and short circuit proof«.

7 CONCLUSION AND RECOMMENDATIONS

Many building integrated PV projects are built to demonstrate innovative applications for PV. They intentionally use new materials and system approaches. The use of innovative materials, such as new module types, or new mounting systems, generally will increase the risk of component failures. These projects are not suited to derive general statements on the reliability of PV components.

Standard PV modules have reached a high quality standard today. They have matured over the last 20 years and show failure rates down to 0.01 % per year. However, there are some brands which exhibit less than stated STC power.
Inverters too, have matured remarkably. Experience from most recent projects shows troublefree operation for 10 years.
Critical are novel electronic components, e.g. inverters, special grid interfaces or ac/dc RCDs. These need some field experience before they work reliably.

Class II modules offer the system designers more liberty when determining the protective measure of their system. Using proper installation techniques string diodes and string fuses can be left out, which results in a simpler and more reliable system.

Based on the reported experience following recommendations can be given:

Select proper components
- use Class II installation equipment.
- use spring loaded „cage clamp“ terminals for all field connections.
- provide drainage opening for condensation water for all outdoor boxes and housings (including inverters).
- consider service of inverter manufacturer for inverter selection.
  – response time ?
  – quick replacement ?
- allow 50 % margin for reduced string voltage, when choosing array voltage and inverter type.

Secure critical issues in contract
- regulate warranty details for equipment, especially custom modules in the purchase contract.
- specify time for inverter repair versus penalty or guaranty of annual yield.

Ensure proper workmanship
- always introduce wires from the bottom side of a junction box
- use strain relief at wire entries, e.g. by cable glands

Ensure proper maintenance

- inspect array regularly, once per year
- clean array regularly, once per year, if soiling is noticed.
- perform an acceptance test with measuring operational string current
- perform a regular check of electric yield, at least monthly.

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