FINAL TECHNICAL REPORT

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TITLE:	Intelligent Performance Check of PV System Operation Based on Satellite Data

PROJECT CO-ORDINATOR: Oldenburg University, Institute of Physics, Energy and Semiconductor Research Laboratory

PARTNERS:
Enecolo AG, Mönchaltdorf, Switzerland
Utrecht University, Utrecht, Netherlands
Meteocontrol GmbH, Augsburg, Germany
Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany

AUTHORS: E. Lorenz, J. Betcke, A. Drews, A.C. de Keizer, S. Stettler, M. Scheider, S. Bofinger, H.G. Beyer, W. Heydenreich, E. Wiemken, W.G.J.H.M. van Sark, P. Toggweiler, G. Heilscher, D. Heinemann

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1 EXECUTIVE PUBLISHABLE SUMMARY, RELATED TO THE PERIOD JANUARY 2005 – OCTOBER 2005

The PVSAT-2 project aims at the assembling of a fully automated service for performance check and failure detection for photovoltaic (PV) systems.

This procedure will reduce the operators running costs by helping to optimise energy yields and system maintenance by daily surveillance. Malfunctions of a grid-connected PV system, e.g. drop out of single module strings, shading by surrounding objects, or inverter errors lead to energy losses that can be high and costly if they remain undetected for a longer period. PVSAT-2 provides a user-friendly, accurate, and reliable method to prevent operators from this trouble.

The PVSAT-2 service consists of the following components developed during the PVSAT-2 project:

1. A low cost hardware device automatically records the actual power output of a PV system and transfers the measured data daily to a central server.
2. Solar radiation is determined from Meteosat-8 images on an hourly basis using an enhanced version of the Heliosat method [Lorenz, 2007]. A further improvement of irradiance information is achieved by a combination with ground data from meteorological stations [Betcke and Beyer, 2004]. Situation specific accuracy information allows for an optimum use of the irradiance data.
3. Based on the irradiance data, the expected yield of a PV system is calculated using a PV simulation model [Beyer et al., 2004].
4. The achieved energy yield and the simulated values are examined daily by the automated failure detection routine [Stettler et al., 2005]. This algorithm decides on the occurrence of a malfunction and identifies typical error patterns that characterize the possible system failure. Furthermore, it informs the operator about the system's performance and, in case of a malfunction, about the most likely failure sources.

The performance of the PVSAT-2 service was evaluated with historic data and in a field test that started in February 2005, including 100 PV systems in Germany, the Netherlands, and Switzerland. Based on these evaluations several improvements have been made in different aspects of the PVSAT-2 procedure. Critical points for the PVSAT-2 service are a correct system description, correct data sheet information, the size of the error bars of the simulated energy yield, and automatic data transfer from the data logger to the server. The field test proved that automatic detection and characterization of failures in PV system performance is possible by using satellite data.

Expected results and exploitation plans

The implementation of the PVSAT-2 routine will serve the photovoltaic solar energy community with high quality solar irradiance data and management tools. The application of the prototype during the test phase proved the effectiveness of the procedure to detect PV system failures.

The deveolped procedure will be offered by the companies Meteocontrol GmbH and Enecolo AG as commercial services. PVSAT-2 will realize an information, data and communication system integrating solar resource data, PV system information and - as a future option - grid data from utilities. This will significantly ease the operational management of photovoltaic solar energy systems.

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Cumulative list of publications

Conference contributions:

Lorenz, E., Betcke, J., Drews, A., Heinemann, D., Heilscher, G., Schneider, M., Toggweiler, P., van Sark, W.G.J.H.M., Wiemken, E., Beyer, H.G.(2005): 'Automatische Ertragsberwachung von Photovoltaikanlagen auf der Basis von Satellitendaten: Evaluierung des PVSAT-2 Verfahrens', 20. Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 09.03.-11.03.2005
Talk

Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., van Sark, W.G.J.H.M., Feige, S., Schneider, M., Heilscher, G., Lorenz, E., Drews, A., Heinemann, D., Beyer, H.G. (2005):'Failure detection routine for grid connected PV systems as part of PVSAT2 project', 20th European Photovolatic Solar Energy Conference & Exhibition, Barcelona, Spain, 06.06.-10.06.2005
Talk

Drews, A., Lorenz, E., Betcke, J., Heinemann, D., van Sark, W.G.J.H.M., Schneider, M., Heilscher, G., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., H.G. Beyer (2005): 'PVSAT-2: An automated performance check for photovoltaic systems based on solar irradiance information from satellite data', 5th Annual Meeting of the European Meteorological Society (EMS), Utrecht, The Netherlands, 12.09.-16.09.2005
Poster Presentation

Beyer, H.G., Prignitz, O., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., de Keizer, C., van Sark, W.G.J.H.M., Schneider, M., Heilscher, G., Lorenz, E., Drews, A., Heinemann, D. (2005):'Performance control for grid-connected PV systems', 13th Sede Boqer Symposium on Solar Electricity Production, Sede Boqer, Israel, 31.10.-01.11.2005
Talk

Invited presentations:

Stettler, S., Toggweiler, P. (2005): 'Automated Failure Detection', 3rd IEA-PVPS Task2 Expert Meeting, Hameln, Germany, 26.09. - 28.09.2005
Talk

Lorenz, E., Drews, A., Heinemann, D. (2005): 'Performance check based on satellite data (PVSAT-2 project)', 3rd IEA-PVPS Task2 Expert Meeting, Hameln, Germany, 26.09. - 28.09.2005
Talk

van Sark, W.G.H.M., Drews, A., Lorenz, E., Betcke, J., Heinemann, D., Schneider, M., Heilscher, G., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., H.G. Beyer (2005): 'PVSAT-2: An automated performance check for photovoltaic systems based on solar irradiance information from satellite data', Dutch Solar Cell R&D Seminar 2005 organized by the Joint Solar Panel, Shell, ECN, Utrecht, The Netherlands, 28.09.2005
Poster Presentation

2 EXECUTIVE PUBLISHABLE SUMMARY, RELATED TO OVERALL PROJECT DURATION

Early detection of faults in grid connected PV systems increases efficiency, reliability, and cost-effectiveness. However, due to the variability of solar irradiation and therefore of the energy yield these faults are difficult to detect for system operators. System surveillance for larger systems is usually performed by using additional hardware such as radiation sensors, data loggers, or other intelligent monitoring devices. Small grid-connected photovoltaic (PV) systems up to 5 kW_p are often not monitored, because advanced surveillance systems are not economical.

Within the PVSAT-2 project a fully automated service for performance check and failure detection for PV systems was developed. In order to provide a low cost service suitable also for small PV systems, the developed procedure is based on inexpensive satellite-derived solar irradiance information that replaces on-site measurements.

This procedure will reduce the operators running costs by helping to optimise energy yields and system maintenance by daily surveillance. Malfunctions of a grid-connected PV system, e.g. drop out of single module strings, shading by surrounding objects, or inverter errors lead to energy losses that can be high and costly if they remain undetected for a longer period of time. PVSAT-2 provides a user-friendly, accurate, and reliable method to prevent operators from this trouble.

Figure 1 shows the structure of the PVSAT-2 service. The service consists of the following components developed during the PVSAT2 project:

1. A low cost hardware device automatically records the actual power output of a PV system and transfers the measured data daily to a central server.
2. Solar radiation is determined from Meteosat-8 images on an hourly basis using an enhanced version of the Heliosat method [Lorenz, 2007]. A further improvement of irradiance information is achieved by a combination with ground data from meteorological stations [Betcke and Beyer, 2004]. Situation specific accuracy information allows an optimum use of the irradiance data.
3. Based on the irradiance data, the expected yield of a PV system is calculated using a PV simulation model suitable for modules of crystalline silicon or thin film cell material [Beyer et al., 2004].
4. There the achieved energy yield and the simulated values are examined daily by the automated failure detection routine [Stettler et al., 2005]. This algorithm decides on the occurrence of a malfunction and identifies typical failure patterns that characterize the possible system failure. Furthermore, it informs the operator about the system's performance and, in case of a malfunction, about the most likely failure sources.

A field test with 100 PV systems in three European countries has demonstrated the benefits and present limitations of the procedure. Furthermore, corrections and improvements of discovered bottlenecks have been introduced.

The developed hardware device WEB'log *light* showed a high quality of measurements, the critical point of this data logger during the field test was the communication with the central server. After several updates during the field test the WEB'log *light* a reliable performance was a achieved for the majority of the systems.

The accuracy of the irradiation data determines the overall accuracy of the whole procedure. The detectability of system failures was investigated for different irradiance data sets. Best results are achieved using a Kriging of differences method combining satellite-derived values and ground measurements. Especially under weather situations as overcast, broken cloud situations, and low sun elevations, the accuracy of the global irradiance increases. Nevertheless, the PVSAT-2 scheme has shown already a good performance in case only satellite data are available. Situation specific confidence intervals increase the potential of the method to detect system malfunctions. Small confidence intervals coincide with high PV power production. This means that the automatic failure detection can be fast under clearsky conditions. For less favorable conditions averaging over longer time periods is necessary.

The evaluation of the simulation of the expected energy yield during the field test revealed that an exact technical description and characterization of the PV system is necessary to achieve reliable results and therefore, a reliable output from the failure detection routine. Especially if registration forms are filled in by laymen slightly wrong specifications cannot always be prevented. Investigations have shown that erroneous described PV systems might be corrected in an initial phase of one month.

The developed failure detection routine combines two approaches, the failure profiling and the footprint algorithm. It has shown its potential in the field test where further optimizations took place. The occurrence of system failures could be detected in a short time while the identification of the failure source took more time in dependence of the predominant weather conditions and of the size of the energy loss. In the process of narrowing down to the most likely failure sources, the detected system malfunctions have been sorted into different failure categories. The footprint algorithm has shown its high potential in identifying reliably the most likely failure sources.

As a result, it can be clearly stated that the PVSAT-2 routine assures economic benefits and prevents owners of small PV systems from energy losses.

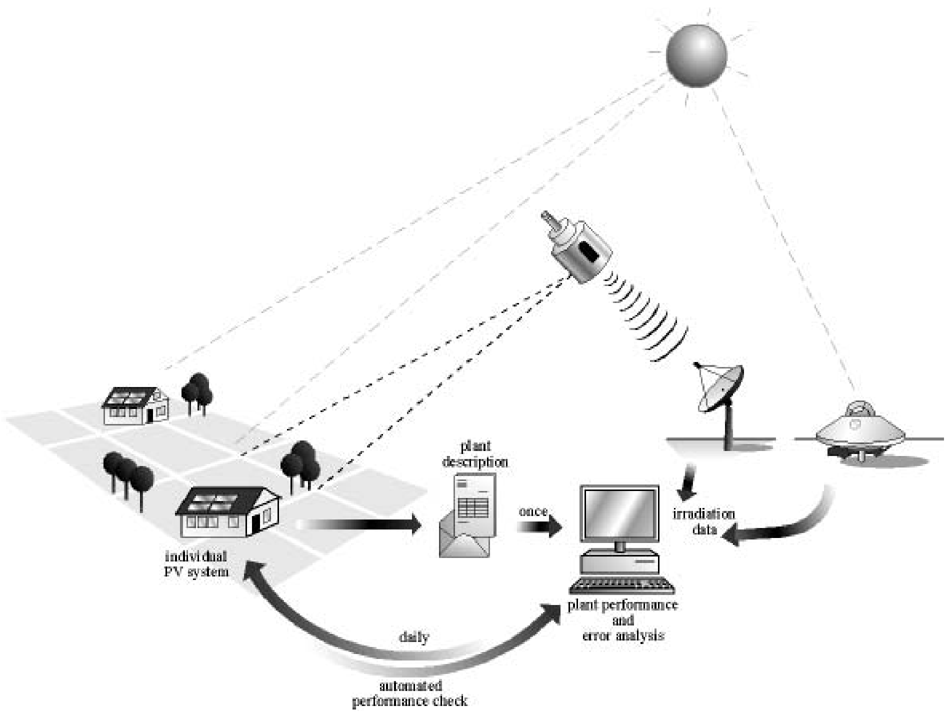

Figure 1: Structure of the PVSAT-2 performance check procedure.

3 DETAILED REPORT, RELATED TO OVERALL PROJECT DURATION

3.1 Background

The number of grid-connected photovoltaic systems in Europe is rapidly increasing. In 2005 645 MWp of photovoltaic systems was installed, which leads to a total installed amount of 1.8 GWp in Europe [EurObserv'ER, 2005]. Many of these systems are small and often not monitored. For larger systems system surveillance is performed with irradiation sensors, data loggers, or other monitoring devices to prevent economic loss due to malfunctioning. This is not economical for small (< 5 kWp) systems. Furthermore, PV laymen might not discover a partial malfunction of their system, since the energy yields are fluctuating with weather conditions. [Jahn et al. 2004] state that on average a failure happens once every 4.5 years for PV systems installed between 1991 and 1994 of which inverters contributed 63 %, PV modules 15 %, and other failures 23 %. Monitoring of small PV systems leads to a rapid discovery of malfunctions. This leads to a higher energy gain and especially in countries with a feed-in tariff also to a financial benefit.

The European project PVSAT, the preceding project to PVSAT-2, addressed this issue by providing operators with a system specific monthly reference yield [Reise et al. 2000]. This reference yield is determined by a generic system model that uses hourly irradiance data from satellite images and individual system descriptions as input. A field test of the PVSAT procedure proved the value of the method in practice, but also showed a limited commitment of clients to a regular comparison of measured and reference yield [Betcke et al. 2001]. Furthermore, it showed that the accuracy of the irradiance input was the limiting factor for the overall accuracy [Betcke et al. 2001].

In the PVSAT-2 project the performance check procedure was further improved by introduction of the following new features:

- A central knowledge-based decision making system will analyse the performance of the PV system on a daily basis, and will be able to detect system failures and its possible causes.
- A low cost hardware device will be integrated into the PV system for automated measurements and communication and the central decision making system. This will increase the reliability of the yield measurements and make the PVSAT-2 application more easy to use.
- The accuracy of the irradiance data will be further improved. With this aim additional on-line ground data will be combined with satellite data using a Kriging of differences interpolation. This method also supplies information on the expected quality of the derived irradiance values, thus supporting the decision making system. Furthermore, new developments in the field of meteorological satellites and an improved diffuse light model will be integrated in the procedure.
- The calculation scheme for the behaviour of modules and MPP tracking will be further improved. Special attention will be paid to the development of models for thin film technologies.

These additions will improve the accuracy, speed of error detection and, userfriendlyness of the procedure.

3.2 Scientific/ technological and socio-economic objectives

PVSAT-2 is a project of different challenges. Scientific and technological as well as socio-economic aspects are well represented. The review reminds of the proposed objectives.

The principle objective of PVSAT-2 is to support the solar energy community in its efforts for increasing the efficiency, reliability, and cost-effectiveness of solar energy systems and improving the acceptability of renewables.

To achieve the goals of the EU energy policy and to accelerate the market penetration of solar energy technologies, improvements in both technological domains (e. g. increase efficiency, achievement of mass production) and in the operation of solar energy systems are necessary.

For improving the operation of PV systems detailed knowledge of the fluctuating energy source solar radiation is an issue of strategic importance for an optimised system performance. In previous work, the use of satellite data for providing irradiance information for the surveillance of grid connected PV systems has already shown its great potential. The introduction of additional components makes this concept a unique system for surveillance, fault diagnosis and control of PV systems capable of managing an unlimited number of installations automatically in the same manner. The combination of satellite data with automatic low-cost on-site production measurements is unique and offers an attractive challenge for the broad low-cost control of the proper functions of grid-connected PV systems.

The components of PVSAT-2 which make them a unique tool for an efficient integration of photovoltaics into the future electricity structure are:

- Addition of a low cost hardware user interface for communication between PV system and PVSAT-2 server based on Internet communication structures.
- Introduction of a client-server decision making system including the satellite-based retrieval of irradiance data, performance analysis of the system on a daily basis and a failure analysis system based on a knowledge base.
- Improved accuracy of satellite-based irradiance estimation in combination with selected ground truth data and introduction of additional knowledge on accuracy.

The added hardware monitoring device will allow for a reliable and precise measurement of the actual production. This avoids typical human errors due to meter readings not done in due time or done incorrectly. The communication between the measurement site and the central server gives the opportunity to use a client-server system using more information for the failure detection decisions. There is also an added value for the set-up of the communication infrastructure. The gathering of performance information at the server and the two-way communication can later be used for new applications in grid management.

The detection of possible failures in PV systems needs expert knowledge in evaluating the performance data. The automated decision making system will include collected evaluation knowledge and will be able to detect the failures on a daily basis depending on the quality input. The failure analysis will also give important hints to the inexperienced user to keep his system at optimal performance thus increasing overall efficiency and reliability of a broad range of systems.

The decision making system will use a step-by-step approach. In a first step the local system can decide on the comparison of the calculated yield from the server and the measured energy production. Advanced steps include a two-way communication with the server and information of nearby located systems or past data of the same system can be used for performance analysis. Using this information, the server can analyse failure patterns and make suggestions with respect to possible failure causes.

The automated decision making system will shorten the time of failure detection thus improving the reliability of the systems and therefore will be of high economic value for the owners of PV systems.

Administration costs are crucial for a surveillance system. These costs have to be significantly lower than the avoided costs of energy losses through system failures. An easy to use multi-channel communication portal will give high flexibility in administration and the possibility of self-administration by the clients will keep the administrative efforts low.

The accuracy of the radiation calculation scheme is dominating the overall accuracy of the PVSAT-2 procedure. This accuracy can be improved through the interpolation with online measured ground data (Kriging of differences) and by the use of an advanced calculations scheme available after the launch of the Meteosat Second Generation (MSG) satellite. This new scheme was developed in cooperation with the European project HELIOSAT-3. Another weak point of the current method is the diffuse radiation modelling which leads to errors when the global irradiance is converted to the mostly tilted planes of PV systems. A revised model will improve the diffuse fraction calculation. For the use within a decision making system additional information on the quality of the solar energy information is highly desirable in order to improve its decisions. Experiences with the HELIOSAT method, which is currently used for the calculation of the solar irradiance, have shown, that the quality differs depending on the weather situation. This information can be used to introduce different thresholds for failure detection and uncertainty figures for the calculated yields.

These measures will provide the solar energy industry and the users of PV systems with a service assuring a system operation within much smaller error margins. The probability of larger system failures will decrease significantly. The main advantages for solar energy users are:

- A daily evaluation of the performance of the PV systems, which ensures shortest breakdown times.
- An intelligent decision making system which will automatically detect system failures and thus avoids losses in the yield of the system.
- An easy Internet-based access to these data sources.

The proposed two-way communication integrated into the PV systems and the measurement of the performance will directly contribute to the Target Action I: Integration of RES and distributed generation in energy supply systems. The increased efficiency and reliability will also reduce operational cost through reduced maintenance. Higher availabilities increase the efficiency of the systems. This will support Target Action L: PV.

The operational PVSAT-2 procedure will rely on modern Information and Communication Technologies (ICTs), as the complete communication between all components will be based on Internet technologies. An increasing share of fluctuating PV power in utility networks calls for information availability and performance of the systems. The two-way communication and the client-server concept can provide this information to the network operators. Therefore, it will support the *Priorities of strategic importance to the EU* in *Exploiting the potential of new ICTs in energy RTD.*

Within the work programme PVSAT-2 will contribute to the Key Action 5: *Cleaner Energy Systems, Including Renewable Energies*, Action Line 5.3: *Integration of new and renewable energy source into energy systems and* Action and Action Line 5.3.1 *Integration of renewable energy sources into the grid and stand alone systems.*

3.3 Applied methodology, scientific achievements, and main deliverables

3.3.1 Introduction

Within the PVSAT-2 project a fully automated service for performance check and failure detection for photovoltaic (PV) systems was developed. The developed procedure is based on satellite-derived solar irradiance information. In conjunction with a simulation model the expected energy yield of a PV system is calculated. The actual actual power output of a PV system is measured with a low-cost hardware and transferred daily to a central server. In case of the occurrence of a significant difference between the simulated and actual energy yield, an automated failure detection routine searches for the most probable failure sources and notifies the operator. The effectiveness of the proposed procedure was verified in a test phase, including tests with historic data and a field test with 100 PV systems in three European countries.

In the following the different components of the PVSAT-2 service - the failure detection routine, the low cost hardware device, the improved irradiance calculation scheme, and the PVSAT-2 prototype - will be described and the results of the test phase will be presented.

3.3.2 WP2000 Development of a Decision Support System for the Automated Performance Check

Introduction

An automated Failure Detection Routine (FDR) compares the measured energy yields with reference energy yields. The reference energy yields are based on satellite-derived data of global irradiation as described in [Betcke, 2004] and [Lorenz, 2007]. If the measured energy yield is significantly lower than the reference energy yield, the FDR analyses the pattern of energy loss (height, duration etc.). This pattern is automatically compared with predefined patterns of frequently occurring failures (as e.g. shading or string defect). The accordance of the actual pattern of energy loss with the predefined failure patterns is used to define which failures are most probable in the actual case and which ones can be excluded. The Failure Detection Routine was described in detail in [Stettler, 2005]. It consists of three different parts:

1. The Failure Detection System
2. The Failure Profiling Method
3. The Footprint Method

The Failure Detection System organizes the whole Failure Detection Routine: it calculates the needed input data, determines if all necessary data are available, decides if the two subroutines (the Failure Profiling Method and the Footprint Method) shall be started and it aggregates the results of the Failure Profiling Method and the Footprint Method.

The Failure Profiling Method investigates the properties of the significant energy loss as height of the energy loss, duration, changes, and correlation with neighboring PV systems. Additionally, it investigates ambient temperature. The findings of this analysis are used to create a failure pattern, which then is compared with different predefined failure patterns of frequently occurring failures. The better the actual failure pattern fits to one of the predefined failure patterns, the higher is the probability that this failure has occurred.

The Footprint Algorithm (see e.g. [Drews et al. 2007]) aims at the identification of also minor energy losses due to shading, permanent power loss, or inverter malfunctions. To detect these types failures an hourly resolution of the input data is required. In order to reduce simulation errors that may be high for hourly values, a special statistical approach was developed considering average values of one, seven, and thirty days. In this way also small system failures may be detected on a daily base for days with small error bars. For less favourable conditions averaging over larger periods reduces errors, and smaller system failures will be detected on a weekly or monthly base.

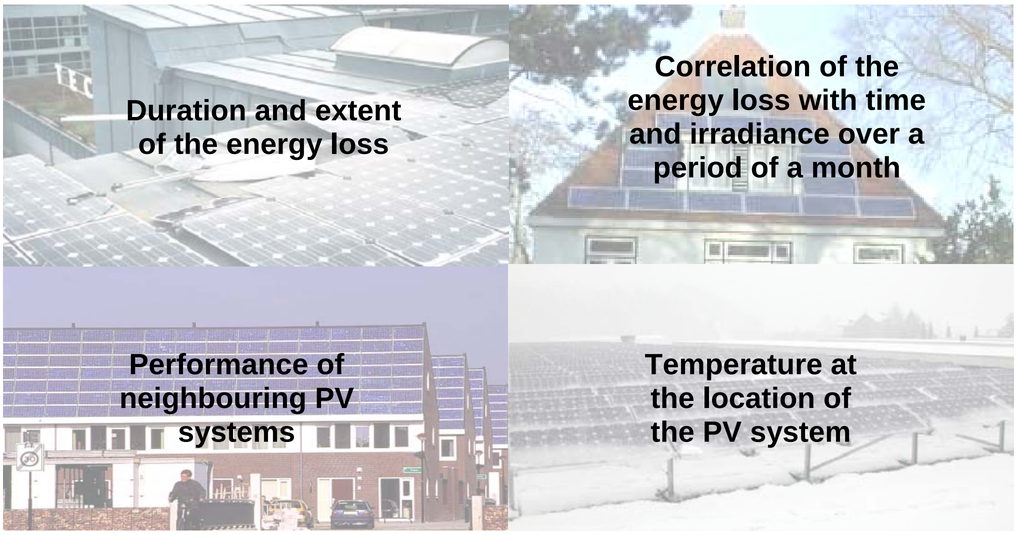

Figure 2: Duration, height and changes in energy loss, behavior of neighboring PV systems and temperature are important aspects considered in the FDR to determine the possibility of different failures

System failures are identified by extraction of error patterns and comparison to typical error patterns. The error patterns are identified by displaying the ratio of simulated to measured power output over the variables ’time’, ’sun elevation’ and ’power output’. The results of the Footprint method are included in the Failure Detection Routine.

Test with historic data

The FDR was intensively checked with data sets of several PV systems in the test phase and with historical data. During these tests, several problems and possibilities for improvements were detected. Most of them could be solved by slightly changing the programming code or the configuration set. The most important improvement was the increase of the reliability interval from 66% to 95% for the calculation of the significant energy loss. Thus, the FDR will start erroneously at only 5% of the days. The FDR was additionally upgraded by including two new failures in the failure list of the FDR.

Test phase with 100 PV systems

The most severe failures in a PV system are total blackouts, which can be caused by a defect inverter or defect control devices as e.g. the main switch. Total blackouts were recognised by the Failure Profiling Method within one day except for days with very low irradiance below 400W/m^2. In cases of total blackout the Failure Profiling Method additionally could exclude all other failures, as e.g. shading or string defect. The other important classes of failures that can be detected by the FDR are constant energy losses, changing energy losses, and snow cover.

Constant energy losses can be caused by string or module defects, but also by degradation or soiling. If a constant energy loss occurs, the Failure Profiling Method can exclude total blackouts, but at most days it still cannot decide if the energy loss is due to a constant or due to a changing energy loss. The reason is, that at low irradiances (i.e. in the morning and afternoon) the uncertainty of the yield simulation is too big to allow a decision whether the energy loss remains constant for the whole day. Constant energy losses are therefore more difficult to distinguish from other types of energy losses like changing energy losses.

Changing energy losses as shading or high losses at low power usually cannot be detected with the Failure Profiling Method, as they occur at low irradiances, which means that the uncertainty of the simulated energy yield is too low to allow an investigation. Therefore, to detect shading the results of the footprint method are integrated in the Failure Detection System.

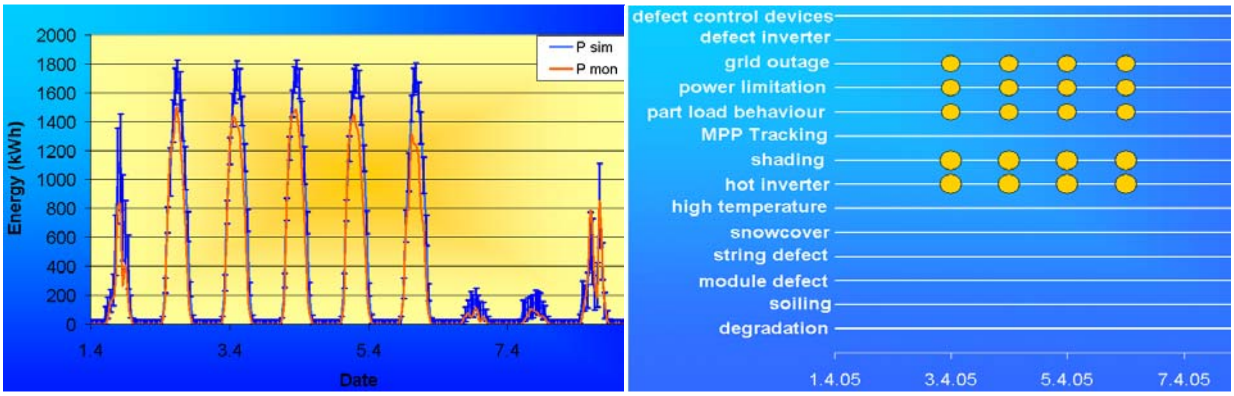

Figure 3: Power limitation at high irradiances in PV system CH-Tessin 3B. Simulated and monitored energy yield in the left picture, results of Failure Profiling in the right picture

In winter months, snow cover is a very frequent source of energy loss for PV systems in Switzerland and in Germany. In all cases where snow cover was detected as the only cause by the Failure Profiling method, a detailed manual analysis supported this result. But as the only information about snow cover in the Failure Profiling Method is ambient temperature, it is not able to distinguish between total blackouts, unknown failures, and snow cover in winter days so far.

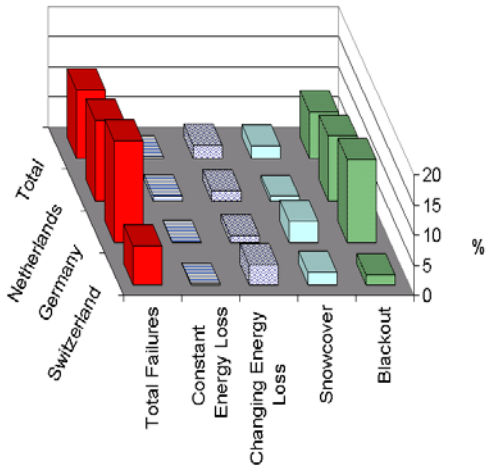

Figure 4: Number of detected failures in % of investigated days.

In the test phase on average in 10% of the investigated days a failure was found. In Germany and the Netherlands most failures were qualified as blackouts. In most of these cases actually no failure had occurred in the PV system but the data transmission from the data logger to the central server did not work. The amount of data transmission problems can be seen when the percentage of blackout in German and Dutch systems is compared with Swiss systems. In Switzerland days with completely missing data were excluded manually and in consequence blackouts were only found in about 1.6% of the investigated days. Though, Swiss PV systems show more failures with changing energy losses than German or Dutch systems. This finding also is most likely an artefact due to problems with the data transmission. The frequency of snow cover also differed between the three countries. This is partly due to the different climates (there is less snow in the Netherlands than in Switzerland and in Germany). In some German systems, snow cover was also “detected” at winter days when no energy yield was transmitted by the logger.

Constant energy losses were detected very seldom in all countries. This is mostly due to the fact that the installed rated power of PV systems with constant energy losses during the whole test phase was adjusted before the analysis with the Failure Detection Routine. In this way, the installed power was reduced for 16% of the PV systems. If this would not have been done, most probably for some of these systems constant energy losses would have been detected.

Results of the test phase

In summary the results show that the FDR only detects a failure, if the measured energy yield is significantly lower than the reference energy yield. This means that erroneous starts of the Failure Detection Routine occur in at most 5% of the days (provided that the measured and reference yields are correct). Total blackouts were detected very fast and also daily energy losses of more than 20% were reliably detected at nice days. Lower energy losses can be detected at days with high irradiance in summer. The FDR not only detects failures but also identifies them. It can distinguish very well between constant energy losses of some percent (degradation, soiling, string or module defect), total blackout (due to inverter defect or defect control devices), and short-time changing energy losses (shading, hot inverter, MPP tracking etc.). Additionally, by considering the ambient temperature it detects snow cover only at cold winter days and hot modules only at hot summer days.

As hinted before, the results of the FDR were only reliable, if the necessary input data (measured and reference yields) were correct. In the test phase it occurred very frequently that the data logger did not send the energy yield to the central server. In these cases the FDR found a total blackout of the PV system and in consequence indicated a defect inverter or defect control devices. Another frequently occurring problem was a wrong system description (wrong azimuth angle, wrong installed power) which leads to wrong reference yields.

As a consequence, the FDR is very suitable in the actual version to detect total blackouts and, at nice days, also daily energy losses higher than 20%. Precondition is correct input data (measured and simulated energy yield). Several different failure classes can be distinguished very well (i.e. total blackout, constant energy losses, changing energy losses, and snow cover). Within one failure class it is very hard to distinguish between individual failures, because the failure patterns are very similar. This will have to be improved in future versions of the FDR as well as a plausibility check of the input data will be necessary.

Outlook

The results of the test phase triggered several ideas about how to improve the FDR. The FDR has to be upgraded in a way that it is capable to distinguish between the two cases “no energy yield produced” and “no data transmitted”.

Although the FDR is very good at distinguishing between the general failure types “constant energy loss”, “changing energy loss”, and “total blackout”, it is very hard to distinguish between failures with very similar failure patterns. For example, the failures degradation and module defect show the same failure pattern: a constant energy loss of a certain percentage. Therefore, the actual version of the FDR will indicate both failures as possible. To enable the identification of individual failures with similar failure patterns, the FDR would need additional methods of investigation (e.g. extended investigation of the correlation of energy loss with temperature and irradiance, refined analysis and comparison with similar and neighbouring PV systems) and more input data (e.g.

alarm signals of the inverter). It might also be a possibility to aggregate failures with similar failure patterns to a single failure category and give out the result for this failure category instead for every single failure.

When showing the results of the FDR to test users it revealed that besides the information about possible failures, the users mainly wanted to know about the severity of the energy losses. But although the FDR calculates the height of the energy loss with different reliability intervals it does not give out this information in the result table. Therefore, in a future version of the FDR the information about the severity of the energy loss should be included in the result table.

3.3.3 WP3000 Development of Intelligent User Interface

The specification and development of the Intelligent User Interface was one of the challenges in the beginning of the PVSAT-2 project. The hardware device is needed to record the energy output and transfer the data automatically to a central database. This user interface has to meet the guidelines of the PVSAT-2 project and the user expectations of the PV market.

The PVSAT-2 requirements were to measure the energy yield and transfer the date automatically to the central server.

A detailed survey has been done to account for user expectations.

The result of this survey was first of all, that 96% of respondents think that a monitoring system is necessary. The motivation for purchasing a monitoring system was quite different, but to get to know the actual yield was the main motivation. Only 30% think that the detection of losses and the optimisation of the yield have main priority. This means that the product has to provide additional features beside of the alarm function.

The statements about the costs differed strongly. The basic acquisition costs for solar monitoring systems should be between 100€ and 500€ for the most respondents. For the regular monitoring costs the users would be willing to pay 5€ per month.

After defining the clear specification of the hardware, a detailed market research has been done. The aim was the evaluation about available components on the market. 42 companies and 90 different products were selected and analysed in detailed. The research showed that there are some devices to measure the energy for low prices, but none of them met the guidelines of the PVSAT-2 project. The development of a specific product was inevitable.

The first prototype of the hardware WEB'log *light* has been developed and tested in the CE-Lap and on specific PV plants. With the results from the test an improved circuit board was realised.

3.3.4 WP4000 Improved Radiation Calculation Scheme

The detectability of system malfunctions with the PVSAT-2 routine is determined by the accuracy of the simulated energy yield based on satellite data. The accuracy of the irradiance input is the limiting factor for the overall accuracy of PV power output simulation ([Betcke et al. 2001], [Beyer et al. 2001]]). An improved irradiance calculation scheme was developed during the PVSAT-2 project. Two complementing approaches were investigated. The Heliosat method [Hammer et al., 2003] to derive global and diffuse irradiance from satellite data was enhanced by introduction of several new features. Furthermore, an approach was presented to increase the accuracy by combining data from accurate, but spatially scarce, ground based pyranometer measurements with the surface covering data derived from satellite images.

Improving accuracy of irradiance calculation by combining satellite and ground data

We investigated if it is possible to increase the accuracy by combining data from ground based pyranometer measurements with irradiance data derived by the Heliosat method from satellite images. The satellite data were derived from Meteosat-7 images with the original version Heliosat method according to [Hammer et al., 2003].

As a reference for the data fusion methods, three interpolation methods were presented: nearest neighbour, gravity interpolation, and Kriging. The latter has the advantage that it provides an estimate for the accuracy of the result. To combine ground and satellite data we introduced interpolation of differences. This means that the difference between ground and satellite value is spatially interpolated, and this interpolated difference is added to the satellite value at the location where the irradiance value needs to be known. A detailed description on the investigated methods and a detailed validation is given in [Betcke, 2004].

The proposed methods have been cross-validated on data sets of monthly, daily and hourly values from Ireland, Germany, the Netherlands, Spain and Sweden. Best results were archived with Kriging for the interpolation methods using only ground data and with Kriging of differences when combining satellite-derived and ground data.

Interpolation of ground data only performed better than Heliosat for monthly values and a distance between ground stations smaller than 55 km.

The overall *rRMSE* achieved by Kriging of differences was in the range of 3.5% to 5.3% for monthly values (improvement: 2% to 3%), 10.6 % to 14.2 % for daily values (improvement: 0% to 2%), and 15.2% to 22.3% for hourly values (improvement: -1.3 % to 1.4%). In all cases substantial error reduction was achieved at low irradiance values.

The error estimate of Kriging and Kriging of differences tended to overestimate the standard deviation. However, the error range containing 95% of the data was estimated fairly accurate.

Improvement of diffuse irradiance calculation

An enhanced approach for the calculation of global and diffuse irradiance based on the Heliosat method was developed in WP4200. A systematic error analysis was performed to identify weak points of the current method and improvements were suggested. Main features of the new approach for the estimation of the global irradiance are the introduction of a variable cloud reflectivity ρ_c and a variability correction for broken cloud situations. Furthermore, an advanced approach for the calculation of the ground reflectivity based on ([Kuhlemann and Hammer 2005]) was developed.

As an additional feature, a geometric correction developed in the framework of vIEM accounts for effects caused by the different viewing angles of sun and satellite. The integration of a new algorithm for detection of snow cover, developed by [Heinicke 2006] allows for a better estimation of the irradiance in the presence of snow cover. A detailed description on the different features of the enhanced approach for the irradiance calculation is given in [Lorenz 2004] and [Lorenz 2007].

The proposed new approach to enhance the irradiance calculation was evaluated for Meteosat-7 and Meteosat-8 in comparison to the original method for about 20 stations of the German weather service (DWD). With the new approach systematic deviations for different seasons and different cloud situations are avoided and a significant reduction of errors is achieved. The evaluation was performed on different time scales, relevant for the PVSAT-2 application. For all timescales best results were achieved for the enhanced method applied to Meteosat-8 data. For hourly irradiance values an *rRMSE* of 18.2% is found, the *rRMSE* of the original Heliosat method for Meteosat-7 was 21.6%. For daily irradiance sums a *rRMSE* of 9.5% is found (before: 11.9 %), and for monthly irradiance sums the *rRMSE* is 3.9% (before: 5.6%).

The improved estimation of the global irradiance also results in a higher accuracy of the diffuse irradiance. An additional enhancement for the diffuse irradiance was achieved by the introduction of a spatial variability correction for the diffuse fraction.

Quality Information on Irradiance Calculation for the Decision Support System

The automated performance check provided by the PVSAT-2 service requires not only high quality irradiance data input, but information on the accuracy of the input as well. This quality information will be used by the failure detection routine and is necessary do decide, whether the difference between calculated and measured power output is caused by the uncertainty of the power output calculation or by system malfunctions. An appropriate characterisation of the expected simulation uncertainties is essential for an efficient application of the failure detection routine. On the one hand error bars should be chosen as small as possible to fully exploit the potential of the method to detect system malfunctions. On the other hand, error bars have to be large enough to avoid erroneous diagnosis of system malfunctions, when actually the system is working well.

In order to provide the required accuracy information a detailed error analysis for the irradiance calculation scheme was performed in WP4300. Based on this accuracy assessment confidence intervals for the calculated power are provided that denote maximum expected errors of the simulation. This is illustrated in Figure 5, where measured and simulated power output and corresponding confidence intervals are displayed for an example PV system for two days in June 2005. Figure 5 shows the high quality of PV simulation for clear sky days with high power production, while for cloudy days, especially for broken cloud situations, larger deviations between measured and simulated values are found. In order to account for this behaviour, error margins in dependence on the weather situation and the sun-satellite geometry were derived. This situation specific accuracy information allows for an optimised use of the irradiance data by the decision support system.

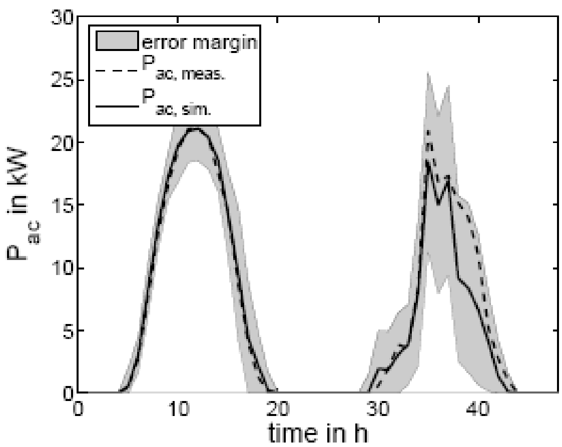

Figure 5: Measured and simulated power output and corresponding confidence intervals for an example PV system for two days in June.

A detailed description on the proposed approach to derive confidence intervals for different time scales is given in [Lorenz 2007b].

In a first step situation specific accuracy information was derived for hourly global horizontal irradiance values. A simple approach was proposed to derive confidence intervals for average irradiance values on different time scales relevant for the failure detection routine and the footprint algorithm, in a second step. Finally, accuracy information for the simulated power output is derived from the respective confidence intervals for global irradiance. Error propagation is applied to account for the uncertainty of satellite-derived global irradiance values. Furthermore, estimations for the uncertainty of the tilt conversion model and the PV system model are incorporated.

The proposed approach to calculate confidence intervals was evaluated for irradiance values on different time scales and for hourly PV system power output. For the evaluation situation specific confidence intervals were analysed with respect to reliability and the mean values of error margins in comparison to constant error margins. The evaluation showed that the situation specific confidence intervals reach the target reliability of 95% for different time scales and for the different classes evaluated by the footprint algorithm. Also the accuracy for different PV system configurations is estimated correctly.

In average, situation specific error margins are smaller than constant error margins for the same target reliability of 95%. On all time scales, especially for hourly and daily values a considerable improvement is found. Hence, the potential to detect system malfunctions is increasing with the use of situation specific error margins. Moreover, the use of weather dependent confidence intervals allows for fast fault diagnosis for clear sky conditions. Since these situations correspond to high power production a fast detection of malfunctions of the PV system is most important. For less favourable conditions a longer evaluation period is necessary to reduce errors by averaging. However, as these condition are related to modest energy production, energy losses in cases of a system failure are limited.

3.3.5 WP5000 Implementation of the PVSAT-2 prototype

Prototype hardware: WEB'log *light*

The hardware development was mainly driven by cost reduction issues to make the system also applicable for small PV systems. The requirements on the hardware were rather hard to handle. The challenge was, to achieve a high performance system with many intelligent features for a very low price.

To reach a very low price the components and the manufacturing had to be optimised. Therefore, the controller and the modem were the main issue. On the other hand the installation and the continuous costs are often underestimated. The new product was designed to reduce also this part of expense by a self installing routine und an intelligent communication functionality. The operational costs were reduced by using the cheep communication which is realised on a Internet platform.

Hundred samples of the hardware WEB'log *light* (see Figure 6) were produced for the field test. Several updates were done during the test phase so that the product is now ready for the market. Since 2006 Meteocontrol GmbH is offering the service with the new hardware on the German PV market successfully.

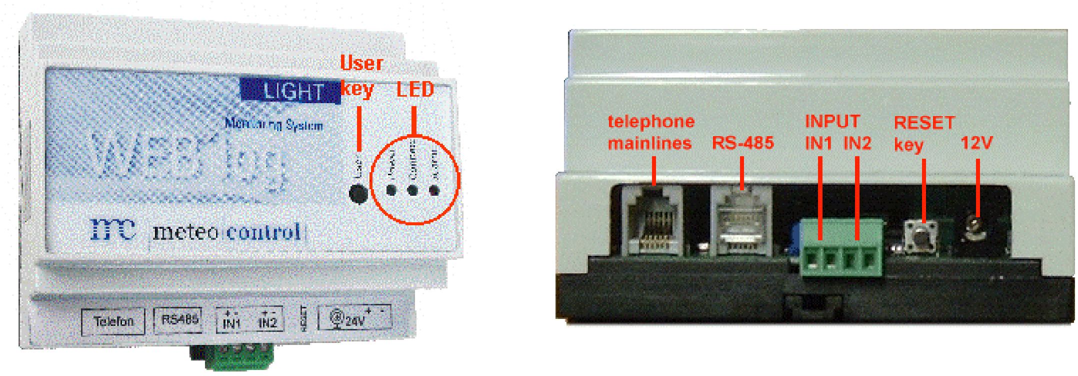

Figure 6: User interface WEB'log *light*.

Prototype of the PVSAT-2 server

The development oft the central sever was the second part of WP5000.

The main task was the implementation of the communication between all components of the PVSAT-2 service. The complete service chain was integrated into existing systems of Meteocontrol GmbH and Oldenburg University.

A reliable service chain that calculates hourly values of global radiation on a daily base provides the basis for the PVSAT-2 server. The improved irradiance calculation scheme, the PV simulation and the decision support system are incorporated to this service chain. In addition to the daily operational service, an automated service for processing historic data was set up. This service was necessary for processing historic data for the test of the decision support system (WP6020), as well as for reprocessing data for the operational service.
The operation of the prototype server was start with irradiance calculation based on satellite data of Meteosat-7. The server has been updated to process satellite data from Meteosat and Kriging of differences interpolation with ground data.

The prototype server for PVSAT-2 was implemented with a distributed structure at Oldenburg University and Meteocontrol GmbH, as illustrate in Figure 7.

There are three main parts of the server:

- The expected power output of the PV system, calculated at Oldenburg University.
- The failure detection routine comparing expected and measured power output, operated by Meteocontrol GmbH.
- A data base at Meteocontrol GmbH contains user specific data necessary for the operation of the PVSAT-2 service.

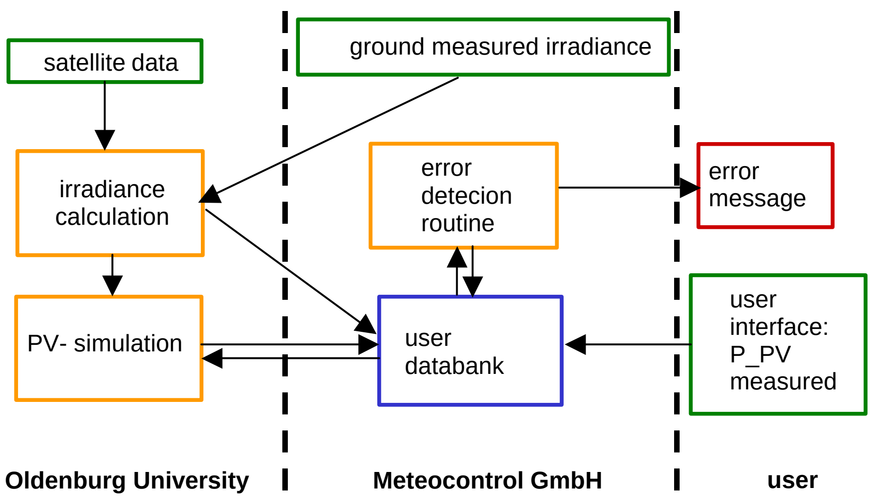

Figure 7: Distributed structure of PVSAT-2 server

A more detailed scheme of the part of the server operated at Meteocontrol GmbH is given in Fig. 8.

The prototype server provides a daily operational processing chain for the on-going performance check of PV systems. Performance tests of the server have shown, that it is possible to handle up to at least 10000 users by one server. An up-scaling to more than 10000 users might require the operation of a second server. A reliable performance of the server was achieved by the implementation of backup solutions for possible errors in the processing chain.

For reprocessing of historic data a second processing chain was implemented, providing time series of irradiance and PV system power output on request.

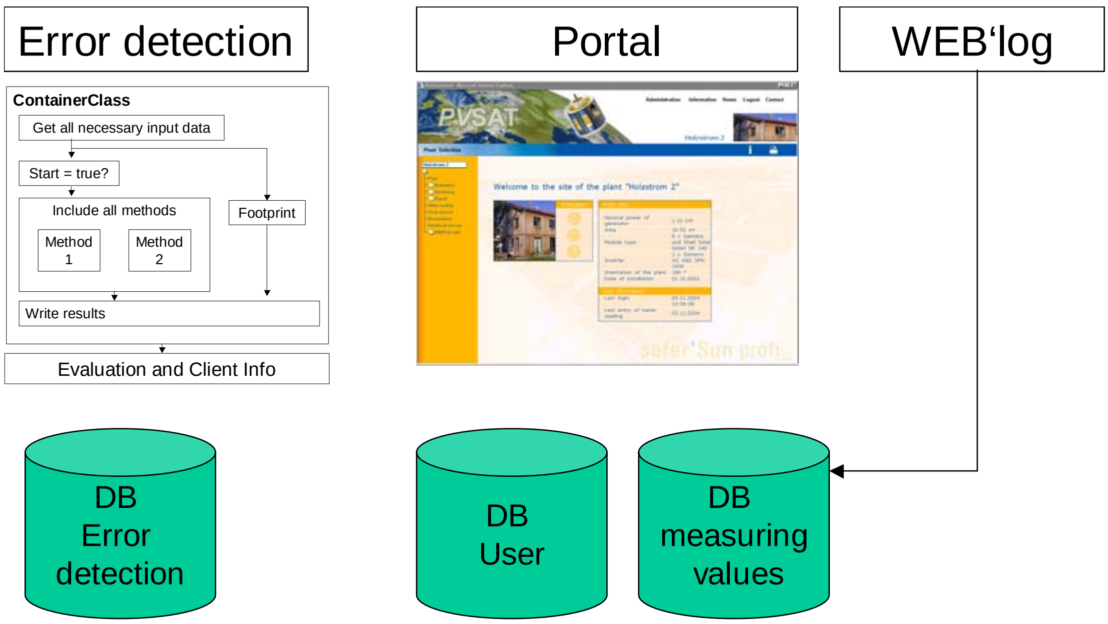

Figure 8: General structure of the PVSAT-2 portal and failure detection.

3.3.6 PV Simulation

In the preceding project PVSAT, emphasis was put on the modelling of modules with cells of the crystalline Silicon (cSi) type. This was justified by the limited range of modules used in the systems participating in the project. For this selection of modules, the application of a model describing the performance of a unique reference specimen had proved to be sufficient.

As PVSAT-2 aims to cover the broader range of module types, including of those with non-cSi technologies the limitations of that approach had to be overcome. Thus a model, able to reflect the efficiency characteristics of both the classic crystalline silicon and the various thin film technologies is required.

A simple procedure for the estimation of the efficiency of PV generators operated under MPP conditions in dependence of irradiance and module temperature $\eta(G,T)$ was proposed. The application of this model was tested for generators with cells made of crystalline silicon (cSi), amorphous silicon (a-Si) and copper-indium-diselenite (CIS).

The test have shown that the proposed simple $\eta_{MPP}(G,T)$ model for the MPP performance of PV generators offers the potential to give a good representation of the dependencies of the system output on irradiance and temperature. It is now included in the operational PVSAT-2 scheme.

3.3.7 WP6000 Validation and Assessment of Uncertainties

Test of Improved Irradiance Data and Resulting System Performance

The quality of the irradiance calculation scheme has been evaluated with respect to the PVSAT-2 application. A comparison of different methodological options to derive irradiance data with respect to the quality of PV simulation results was performed. The results were published in [Drews et al, 2006].

Three different irradiance data sets were evaluated:

- Irradiance data derived from the Meteosat-7 satellite
- Irradiance data derived from the Meteosat-8 satellite
- Meteosat-8 based irradiance data set, refined by combination with ground data

The comparison was performed for a test set of three well-monitored PV systems located in Southern Germany, where additional information such as irradiation measurements on the tilted plane was available.

The comparison of three different data sets has shown that combing satellite data with ground measurements leads to best results. Especially during wintertime, a large improvement is found when refining satellite data by ground measurements.

The accuracy of the irradiance calculation scheme changes with the predominant weather situation; under clear sky conditions the errors are low, while they increase under cloudy skies. This determines the quality of the PV simulation and finally the period of time that is needed to detect a failure. A minor energy loss of less than 15% can be detected using only satellite data during the summertime by examining the monthly power production. Under clear sky conditions a failure with 15% energy loss can be recognized also on the daily time scale. Under broken cloud conditions the detection of a malfunction takes more time. During wintertime energy losses have to be larger than 30% to be detected.

Test of Decision Support System Using Historic Data

In WP 6020 the performance of the Failure Detection Routine was tested by making use of historical datasets. Datasets containing the measured energy yields of 21 well-known and well-described Dutch and German systems were used to analyze the quality of the energy yield simulation. Also the Failure Detection Routine was tested for these systems. For all systems a minimum of one-year data was analyzed.

For most of the analyzed systems measured irradiance of either a pyranometer or a reference cell was available. The quality of the error forecast of the irradiance simulation was more than sufficient; between 97 and 100 % of the measured hourly values of irradiance were within the range of the simulated value plus or minus the predicted error (2 times the standard deviation σ of the errors). On basis of a normal distribution 95 % of the values are supposed to fall within the value $\pm 2\sigma$. The bias for irradiance measurements was between –5% and +8 %. This high value could possibly be caused by the quality of the irradiance measurements by reference cells. The daily *RMSE* of the irradiance varied between 11% and 16% for systems with a smaller tilt angle ($< 40^o$). The hourly *rRMSE* varied between 25% and 34% for these systems. For the high tilt systems a daily *rRMSE* of up to 20%, and a hourly *rRMSE* of up to 40% is found.

The simulated energy yields were correct for several systems, but needed to be adapted for other systems. For several of the studied systems the average flash test power instead of the rated installed power was used. This resulted in a correct high quality simulation. For several other well functioning systems the rated installed power had to be adapted. Of the well functioning systems between 96% and 98.5% of the measured hourly values were within the range of the simulated energy yield ± 2σ. This means that the quality of the energy yield simulation is more than sufficient with the given error bars. Special attention should be paid to the system description though.

For one of the German systems two out of 14 modules were disconnected for a continuous period of three months from half November to half February. This was not detected by the footprint algorithm or the failure profiling method, because the error bars of the hourly and daily simulated energy yield are too large for that in winter. The accuracy of the simulation is much better in summer. Shading was detected by the footprint algorithm for several systems. Also power limitation was detected by the footprint.

The failure profiling method detected several failures. In case of a system with a total blackout, this was always detected, when the irradiance was not extremely low. Also grid outage is pretty well detected. Furthermore one of the studied systems had an overheated inverter on several days in summer. This was detected by the failure profiling method if the resulting energy loss was significant. Also snow was detected for several systems if the irradiation on the concerned day was large enough. Only few false positives were detected with the failure profiling method due to a bad simulation day. This only happens once every few months.

During the historic testing phase the footprint algorithm for shading was improved. Also several changes have been implemented in the failure profiling method. The testing proved that failures causing a significant energy loss are detectable by the two methods. This depends very much on the confidence intervals, which are large in winter and smaller in summer. Also deviation from datasheet behavior might cause some problems.

Field Test and Overall Quality Assessment

The field test aimed at verifying the effectiveness and accuracy of the entire PVSAT-2 routine under field conditions. To that end 100 PV systems in Germany, the Netherlands, and Switzerland were monitored during a field test. The diversity in module and inverter types and in system sizes was high. The average system size ranged from 1.3 kWp for the 29 Dutch systems, via 4.7 kWp for the 35 German systems up to 7.3 kWp for the 36 Swiss systems. There were 57 different module types and 38 different inverter types present in the field test.

Due to some delay in the development of the hardware the test phase did not run for the intended full year, but from early February 2005 up to September 2005. Since not all of the PVSAT-2 hardware, the WEB'log *light,* functioned during this period, only 40 systems with measured energy yield data from the WEB'log *light* are analyzed. Additional data of 60 systems with a different measurement unit was used for analyzing the PVSAT-2 method. The PVSAT-2 hardware reported the 15-minute yield of the test user's PV systems every day to the server. The Decision Support System (WP 2000) performed the comparison between the measured and simulated hourly yields of the PV system. The results of the Failure Detection Routine were analyzed and checked thoroughly.

During the field test several improvements have been made in different aspects of the PVSAT-2 procedure. Several updates of the software of the WEB'log *light* have been implemented in the field test systems. Further improvements have been made in the simulation of the hourly energy yield. The quality of the Failure Detection Routine has increased by improving several features and parameters in the algorithm and by introducing additional failure types.

The development of the WEB'log *light* shows that sufficient time is needed to develop a succesful product. The quality of the measurements of the WEB'log *light* is high, but the critical point of the data logger is the communication via the telephone line with the server. Several initial problems e.g. overflowing of the data buffer were solved during the test phase by implementing new software. For some systems there were continuous problems with calling behavior and transfer of data via the WEB'log *light.* At the end of the test phase the majority of the WEB'log *lights* worked flawlessly.

Also with other types of data loggers automatic transfer of data from the PV system to the central server proved to be a problem. Other problems for some of those data loggers were the necessity of human interference for transferring the data to the server and non-hourly data logging. For the PVSAT-2 routine it is important to have reliable hardware, which reliably logs hourly values at the full hour with time synchronization and which can send measurement data to the server once a day automatically and without transmission problems.

A correct simulation of the reference hourly energy yields with a correct forecast of the standard errors is important. The simulation of the hourly energy yields during the test phase was found to be mostly correct if the system description and the datasheets of the modules and inverters were correct. A couple of changes had to be introduced in the system description to get a matching simulation. The azimuth of 23 of the 100 systems had to be corrected to get a matching simulation. On a daily basis the difference between measured and simulated energy yield as a result of an azimuth error is quite small, but since the footprint algorithm works on an hourly basis, an azimuth error can cause an indication for shading. Furthermore, for at least one system the mounting type was not specified correctly, which resulted in a bias, which was more than 7% higher than for the correct mounting type. For 28 of the systems the rated power had to be adapted. There are several reasons, which justify an adaptation of the installed power. Among these is the tolerance in rated power for the modules and inverters on the datasheet. Furthermore, for one of the German systems in the test phase there were wrong efficiencies of the inverter and higher cabling losses than assumed. In those cases it is not an ideal solution to adapt rated power, but with a lack of time for detailed investigation it is practically achievable. In theory it should be possible to automatically adapt the parameters used for the simulation. Therefore, knowledge on the initial functioning of the system is needed.

The Failure Detection Routine consists of two failure detection mechanisms: the footprint algorithm and the failure profiling method. Different failures occurred during the field test in the 100 studied systems. Amongst those were shading, string error, total blackout, power limitation, overheating of the inverter, and snow.

The footprint algorithm is designed to detect three different failure types: shading, permanent power loss, and power limitation. All these failure types were present in the test phase. Elevation dependent shading is detected if shading takes place at low sun elevations. This means that the shading mostly should take place in the first or last hours of sunshine during the day. This type of shading is often correctly detected by the footprint algorithm, even for minor shading. A disadvantage of the method is that shading during other periods, e.g. in mid-afternoon will not be detected. A future option is to define new, different footprints, which could do so. Permanent power loss is detected for a constant energy loss. The energy loss should be larger than circa 20 % to be detected in summer. For a Dutch system of which one out of six inverters was defect from the end of March onwards (17 % energy loss), this failure was detected constantly for a thirty day period after mid June. Power limitation is detected if there is an energy loss at high power. This is detected very well.

The failure profiling method detects a failure if the daily measured energy yield is significantly lower than the daily simulated energy yield. After this start criterion is met, it starts identifying the failure type. The failure profiling method almost always detects total black out, be it in the form of a grid outage (blackout for a couple of hours), defect control devices or a total blackout. Only on days with very bad weather this is not detected. One of the problems that occur is that a lack of input data, because of a problem with a data logger is identified as a total blackout.

Furthermore, the failure profiling method distinguishes between a constant energy loss of a certain percentage and energy losses that change during the day. An example of a constant energy loss is e.g. a string error; this is detected if the energy loss is significant on a daily basis. In the Dutch system with one out of six defect inverters the energy loss was only detected on days with very nice weather. Other sources for a constant energy loss are module defects, degradation, and soiling. For the failure profiling method it is hard to distinguish between different types of constant energy loss, so in case of a constant energy loss, all of these failure types are returned as possible causes. Changing energy loss is for example shading, power limitation, MPP tracking, and an overheated inverter. Also distinguishing between these failure types is very hard for the failure profiling method. Shading is identified for several systems in the field test. Lastly the failure profiling method also considers the ambient temperature, which is used to identify the failure types: snow cover and overheated modules. Snow cover was correctly detected for several systems.

Finally both methods were integrated in the Failure Detection Routine. The field test proves that automatic detection and characterization of failures in PV-system performance is possible by using satellite data. Critical points turned out to be a correct system description, correct datasheet information, the size of the error bars of the simulated energy yield and automatic data transfer from the data logger to the server.

3.4 Conclusions

A remote performance check including an automated failure detection routine for PV systems has been developed within the PVSAT-2 project. The procedure is based on satellite-derived irradiation data, which is used to simulate the energy yield of a PV system. Improvements on the quality of the satellite-derived irradiance information have been achieved. A PV simulation model suitable for modules of crystalline silicon or thin film cell material has been proposed. The developed automated failure detection routine detects the occurrence of a failure and identifies the most probable causes. The field test with 100 PV systems has demonstrated the benefits and present limitations of the procedure.

The accuracy of the irradiation data determines the overall accuracy of the whole procedure. The detectability of system failures was investigated for different irradiance data sets. Best results were achieved using a Kriging of differences method combining satellite-derived values and ground measurements. Especially under weather situations as overcast, broken cloud situations, and low sun elevations, the accuracy of the global irradiance increases. Nevertheless, the PVSAT-2 scheme has shown already a good performance in case only satellite data are available. Situation specific confidence intervals increase the potential of the method to detect system malfunctions. Small confidence intervals coincide with high PV power production. This means that the automatic failure detection can be fast under clearsky conditions. Less favorable conditions need averaging over longer time periods.

The evaluation of the simulation of the expected energy yield during the field test revealed that an exact technical description and characterisation of the PV system is necessary to achieve reliable results and therefore, a reliable output from the failure detection routine. The field test has shown that errors in the PV system description occur quite frequently at field conditions. An initial phase of one month is recommended to automatically adapt erroneous PV systems descriptions.

Also the performance of the hardware devices ‘WEB’log *light’* was evaluated and improved during field test. After several updates the majority of the WEB’log *lights* worked without any problems and the product is now ready for the market.

The automated failure detection routine is combining two approaches, the failure profiling and the footprint algorithm. The performance of the failure detection routine has been evaluated and further improved in the tests using historical data of well-monitored PV systems and during the field test. The size of the error bars determines the detectability of system malfunctions. If the daily irradiation is high, system failures can be detected in a very short time by both the failure profiling and the footprint method. The failure profiling may detect a larger number of different failure types than the footprint, though mostly only the failure category can be clearly identified. Additional information on the temperature helps to better identify failures that are related to temperature, e.g. snow cover. The strength of the footprint algorithm lies in the evaluation on different timescales. In this way for days with high irradiance and small confidence intervals system failures may be detected on a daily base. For less favorable conditions errors are reduced by averaging over larger periods, and smaller system failures will be detected on a weekly or monthly base. A clear identification of the failure types 'shading', 'permanent power loss', and 'power limitation' is possible.

As a result, it can be stated that the PVSAT-2 routine assures economic benefits and prevents from energy losses, not only valuable in countries with a granted feed-in tariff. It helps to integrate PV as a reliable energy source into the growing mix of renewable energies supplying the energy of our future.

The PVSAT-2 procedure is commercially offered under the product name SPYCE (www.spyce.ch) by Enecolo AG, Switzerland and by Meteocontrol GmbH, Germany under the name safer'Sun Satellite (www.meteocontrol.de).

3.5 Dissemination and exploitation of the results

3.5.1. Dissemination

Target group for the commercial use of the PVSAT-2 service are owners and operators of small and medium range PV systems between one and 5kW as well as customers that run larger systems.

The results of PVSAT-2 are distributed via the PVSAT-2 website, by presentations on conferences, and by publications in scientific journals.

Website
As proposed in work package 7000, a web page (www.pvsat.com) has been established to inform industrial and scientific users about PVSAT-2.

The pages contain information about the aim of the project, methods, benefits for solar energy applications, publications, and participating groups. They are divided into two parts: one for the general public and a closed and protected area for the use of the project partners only. These internal pages are used for project management, document and information exchange between the partners.

Contents

- The page *home* contains a brief introduction of the project – use, existing features, and aims.
- The *project* page contains the official description of the project as written in the proposal.
- *PVSAT-2 procedure* gives a step by step overview over the whole procedure. Details of methods can be found in sub links. With proceeding work and results, more sub links will follow to complete a detailed description.
- Under *pvsat-1* a summary of the PVSAT project (EU JOULE-III program, JOR3-CT98-0230) is given.
- *Publications* lists scientific publications and conference contributions. Most of them can be downloaded there.
- At *InfoPackage* all talks as given in the two public workshops informing about the project and its achievements can be downloaded.

- *Partners* lists the contributing partners of the project with names, addresses, telephone numbers, emails, etc. A click on the logos will lead the user to the individual web pages of the partners.
- *For members only* is a link to the internal pages of the project. Right now all the documents concerning the preparation of the proposal, minutes and the presentations from the meetings are collected here.

Conference contributions

PVSAT-2 was presented at several conferences during the complete duration of the project. The attended conferences are listed in section 6.6. ‘Literature produced’.

Workshop on PVSAT-2

Two workshops on PVSAT-2 were organized, which addressed potential users of PVSAT-2. The PVSAT-2 method, products, and potential given by the consortium and contributions from users on One of the workshops on PVSAT-2 and its use in solar energy applications was held during the ‘20th European Photovoltaic Solar Energy Conference & Exhibition’ in Barcelona, Spain, 06.06.-10.06.2005. The second workshop took place during the Intersolar 2005 in Freiburg on June 24th.

Information package

An information package was prepared to inform potential users, customers, and operators of the PVSAT-2 software. The package is offered at the PVSAT-2 web pages www.pvsat.com for download. It has also been distributed on the workshops in paper form.

3.5.2. Exploitation of results

Meteocontrol GmbH: Safersun Satellite

Meteocontrol GmbH is offering the PVSAT-2 service commercially under the product name “safer’Sun satellite” (www.meteocontrol.de).

Enecolo AG: Spyce

Enecolo AG is commercially offering a performance check for PV systems based on PVSAT-2 under the product name “SPYCE” (www.spyce.ch).

Long-term time series of irradiance for solar energy applications

The improved irradiance calculation scheme developed within PVSAT-2 is applied also for the processing of long-term time series that are offered for several solar energy applications:

- Planning and sizing of PV systems
- Site audits
- Investigation of long term performance of PV systems
- Time series of direct normal irradiance for planning of solar thermal power plans

CM-SAF

The Satellite Application Facility on Climate Monitoring (CM-SAF) aims to generate and archive high quality data to monitor the global climate, analyse and diagnose climate parameters to understand climate change, to provide input for climate models and to validate simulation models. CM-SAF is part of the EUMETSAT funded SAF network. It is based at the Headquarters of the Deutscher Wetterdienst (DWD) in Offenbach, Germany.

The improved software to calculate cloud index images developed within PVSAT-2 will be implemented at CM-SAF in Offenbach, Germany.

vIEM

The Virtual Institute of Energy Meteorology (vIEM) addresses research at the interface between energy systems and meteorology. vIEM is run jointly by the German Aerospace Center (DLR) and the University of Oldenburg. In its initial phase, the institute is supported by the ‘Impuls- und Vernetzungsfonds’ of the Helmholtz Association of National Research Centers.

Further research on methods for solar irradiance calculations from satellite images integrating the developments during PVSAT-2 will take place within vIEM.

ENVISOLAR

ENVISOLAR is dedicated to the development of the market using information on the solar resource for planning and operations of solar energy systems. ENVISOLAR has funded by the ESA Earth Observation Market Development project. The PVSAT-2 based service SPYCE was implemented as a service for plant management for small PV systems. A large number of market trials performed with key customers (plant operators, plant owners, financial investors, energy suppliers) to further improve the operational services run by commercial partners in ENVISOLAR.

IEA SHC Task 36 "Solar Resource Knowledge Management"

The IEA SHC Task 36 "Solar Resource Knowledge Management" is an international programme, which coordinates worldwide activities to develop, improve and standardize methods to derive solar resources. The Task is lead by the IEA Solar Heating & Cooling Programme (SHC). VIEM is contributing mainly to the research part of this task, Subtask C "Inproved techniques for solar resource characterization and forecasts".

Further research on methods for solar irradiance calculations from satellite images in the framework of vIEM integrating the developments during PVSAT-2 will contribute to the IEA Task.

3.6 Literature produced

2004

Conference contributions:

Heilscher, G., Schneider, M., Betcke, J., Drews, A., Heinemann, D., Lorenz, E., Toggweiler, P., von Sark, W.G.J.H.M., Wiemken, E., Beyer, H. G.(2004): 'Satellitengestuetzte Ertragsueberwachung mit automatischer Fehlererkennung fuer kleine und mittere Photovoltaikanlagen', 19. Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 11.03.-13.03.2004.
Poster Presentation

Beyer, H. G., Schondorf-Rother, M., Betcke, J., Drews, A., Hammer, A., Heinemann, D., Lorenz, E.(2004): 'Ertragsberechnung fuer PV-Anlagen in Brasilien ueber das PVSAT Verfahren', 19. Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 11.03.-13.03.2004.
Talk

Stettler, S., Toggweiler, P. (2004): PVSAT-2 – satellitengestuetztes Monitoring von netzgekoppelten PV-Anlagen, 5. Nationale Photovoltaik-Tagung, Zurich, Switzerland, 25.03.-26.03.2004.
Poster Presentation

Lorenz, E., Betcke, J., Drews, A., Heinemann, D., Toggweiler, P., Stettler, S., van Sark, W.G.J.H.M., Heilscher, G., Schneider, M., Wiemken, E., Heydenreich, W., Beyer, H. G.(2004): 'PVSAT-2: Intelligent Performance Check of PV System Operation Based on Satellite Data', 19th

European Photovolatic Solar Energy Conference & Exhibition, Paris, France, 07.06.-11.06.2004.
Poster Presentation

Beyer, H. G., Betcke, J., Drews, A., Heinemann, D., Lorenz, E., Heilscher, G., Bofinger, S.(2004): 'Identification of a General Model for the MPP Performance of PV-Modules for the Application in a Procedure for the Performance Check of Grid Connected Systems', 19th European Photovolatic Solar Energy Conference & Exhibition, Paris, France, 07.06.-11.06.2004.
Talk

Drews, A., Betcke, J., Lorenz, E., Heinemann, D.,Toggweiler, P., Stettler, S., Rasmussen, J., van Sark, W.G.J.H.M., Heilscher, G., Schneider, M., Wiemken, E., Heydenreich, W., Beyer, H. G.(2004): 'Intelligent Performance Check of PV System Operation Based on Satellite Data', EUROSUN (ISES Europe Solar Congress) Freiburg, Germany, 20.06.-23.06.2004.
Talk

Betcke, J., Beyer, H.G. (2004): 'Accuracy improvement of irradiation data by combining ground and satellite measurements', EUROSUN (ISES Europe Solar Congress) Freiburg, Germany, 20.06.-23.06.2004.
Poster Presentation

Beyer, H.G., Heilscher, G., Bofinger, S. (2004): 'A robust model for the MPP performance of different types of PV modules applied for the performance check of grid-connected systems', EUROSUN (ISES Europe Solar Congress) Freiburg, Germany, 20.06.-23.06.2004.
Talk

2005

Conference contributions:

Lorenz, E., Betcke, J., Drews, A., Heinemann, D., Heilscher, G., Schneider, M., Toggweiler, P., van Sark, W.G.J.H.M., Wiemken, E., Beyer, H.G.(2005): 'Automatische Ertragsberwachung von Photovoltaikanlagen auf der Basis von Satellitendaten: Evaluierung des PVSAT-2 Verfahrens', 20. Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 09.03.-11.03.2005.
Talk

Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., van Sark, W.G.J.H.M., Feige, S., Schneider, M., Heilscher, G., Lorenz, E., Drews, A., Heinemann, D., Beyer, H.G. (2005):'Failure detection routine for grid connected PV systems as part of PVSAT2 project', 20th European Photovolatic Solar Energy Conference & Exhibition, Barcelona, Spain, 06.06.-10.06.2005.
Talk

Drews, A., Lorenz, E., Betcke, J., Heinemann, D., van Sark, W.G.J.H.M., Schneider, M., Heilscher, G., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., H.G. Beyer (2005): 'PVSAT-2: An automated performance check for photovoltaic systems based on solar irradiance information from satellite data', 5th Annual Meeting of the European Meteorological Society (EMS), Utrecht, The Netherlands, 12.09.-16.09.2005.
Poster Presentation

Beyer, H.G., Prignitz, O., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., de Keizer, C., van Sark, W.G.J.H.M., Schneider, M., Heilscher, G., Lorenz, E., Drews, A., Heinemann, D. (2005):'Performance control for grid-connected PV systems', 13th Sede Boqer Symposium on Solar Electricity Production, Sede Boqer, Israel, 31.10.-01.11.2005.
Talk

Invited presentations:

Stettler, S., Toggweiler, P. (2005): 'Automated Failure Detection', 3rd IEA-PVPS Task2 Expert Meeting, Hameln, Germany, 26.09. - 28.09.2005.
Talk

Lorenz, E., Drews, A., Heinemann, D. (2005): 'Performance check based on satellite data (PVSAT-2 project', 3rd IEA-PVPS Task2 Expert Meeting, Hameln, Germany, 26.09. - 28.09.2005.
Talk

van Sark, W.G.H.M., Drews, A., Lorenz, E., Betcke, J., Heinemann, D., Schneider, M., Heilscher, G., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W., H.G. Beyer (2005): 'PVSAT-2: An automated performance check for photovoltaic systems based on solar irradiance information from satellite data', Dutch Solar Cell R&D Seminar 2005 organized by the Joint Solar Panel, Shell, ECN, Utrecht, The Netherlands, 28.09.2005
Poster Presentation

2006

Contributions to monographs:

Beyer, H.G., Lorenz, E., Betcke, J., Drews, A., Heinemann, D., de Keizer, A.C., vanSark, W.G.J.H.M., Feige, S., Bofinger, S., Schneider, M., Heilscher, G., Stettler, S., Toggweiler, P., Wiemken, E., Heydenreich, W. (2006): 'Monitoring of solar energy systems in large scale - the project PVSAT-2', In: Solar Resource Knowledge for Management of Renewable Electricity Generation, Editors: E.D. Dunlop, L. Wald, M. Suri, Nova Science Publishers, Hauppauge NY (USA), ISBN: 1-59454-919-2.

Conference contributions:

Prignitz, O., Beyer, H.G. (2006): 'Vom Datenblatt zum Systemertrag – zur realistischen Abbildung der Systemverluste in kleinen netzgekoppelten PV-Systemen', 21. Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 08.03.-10.03.2006.
Talk

Stettler, S., Toggweiler, P. (2006): 'Ertragsoptimierung dank automatischer Fehlererkennung', 21. Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 08.03.-10.03.2006.
Poster

van Sark, W.G.J.H.M. et al. (2006): 'PVSAT-2: 'An automated performance check for building integrated photovoltaik systems based on solar irradiance information from satellite data', 2nd International Solar Cities Congress 2006, 03.04.-06.04.2006, Oxford, Great Britain.
Talk

Drews, A. et al. (2006): 'Remote performance check and automated failure identification for grid-connected PV systems – results and experiences from the test phase within the PVSAT-2 project', EuroSun2006, Glasgow, Great Britain, 26.06.-29.06.2006.
Talk

de Keizer, A.C. et al. (2006) :'Results of field test of satellite-based PV performance check', 21. European Photovoltaiv Solar Energy Conference and Exhibition, September 2006, Dresden, Germany
Talk

2007

Journal papers:

Drews, A. et al. (2007): 'Monitoring and remote failure detection of grid-connected PV systems based on satellite observations', Solar Energy **81**, 548–564.

van Sark W. et al (2007):'Automated performance control for grid-connected photovoltaic systems employing satellite data', Energy and Buildings (in press).

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[Betcke, 2004] J. Betcke (2004): *Accuracy improvement of irradiation data by combining ground and satellite measurements.* Deliverable D 4.1 PVSAT-2: Intelligent Performance Check ofPV System Operation Based on Satellite Data, Contract Number: ENK5-CT-2002-00631.

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Deliverable D 4.3 PVSAT-2: Intelligent Performance Check of PV System Operation Based on Satellite Data, Contract Number: ENK5-CT-2002-00631.

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