PVSAT-2: RESULTS OF FIELD TEST OF THE SATELLITE-BASED PV SYSTEM PERFORMANCE CHECK

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ABSTRACT: Within the EU funded project PVSAT-2 an automated performance check for grid-connected PV systems has been developed. Measured energy yield and simulated yield that is based on satellite-derived irradiation data, are used for the automatic detection of malfunctions in a PV system. It is especially suited for small (< 5 kWp) systems to help avoiding the use of expensive monitoring equipment. The designed method was evaluated for 100 small PV systems in a field test that took place from February to September 2005. We found that incorrect system descriptions caused inaccurate simulations for several systems; solutions are proposed in this paper. The effectiveness of the failure detection is determined by the accuracy of the irradiation information. The uncertainty in the simulated energy yield can be high for cloudy weather situations and at low sun elevation. Under these weather conditions it is more difficult to detect a malfunction than under clear sky conditions. On days with a high irradiation, such as clear sky days in summer, a daily energy loss of circa 15 % can be identified within a day.
Keywords: PV system; performance; monitoring

1 INTRODUCTION

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 [1]. The large majority of these systems are small and often not monitored. Many larger systems use system surveillance 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 [2] states 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.

Therefore, within the PVSAT-2 project a low-cost and reliable method was developed to automatically and daily check the performance of a PV system. Irradiance values are determined from meteorological satellite data, thereby excluding costs for use of relatively expensive (installation of) reference cells. The measured and simulated energy yields are automatically compared, thereby excluding expensive operator time to analyse measurements. During the last year of the project the effectiveness and quality of the PVSAT-2 routine was thoroughly checked in a field test; the results will be presented here. In section 2 an overview of the methodology and the set up of the field test is presented. In section 3 the quality of the simulation of the energy yield is discussed, also some examples of the effectiveness of the failure detection routine in the test phase are given. The conclusions are presented in section 4.

2 METHODOLOGY

2.1 General PVSAT-2 methodology

In Figure 1 the set up of the PVSAT-2 routine is shown. Hourly values of solar irradiance are derived from Meteosat-7 (during the development and test phase) and Meteosat-8 (for the marketed product) satellite images. A description of the system characteristics (tilt, azimuth, module types, inverter, latitude, longitude, distance of system to roof) together with hourly irradiation and temperature information is used to calculate a reference hourly energy yield [3]. This is compared to the measured energy yield by a 'failure detection routine', which in a first step determines, if a failure occurred. In the second step it identifies possible causes for the malfunction [4]. The whole routine is fully automated; monitored energy yield is sent automatically by a data logger to a central server. There the failure detection routine runs automatically every day. The owner of the PV system can check the performance of his or her PV system via an Internet communication portal; feedback is provided in case of detection of a malfunction.

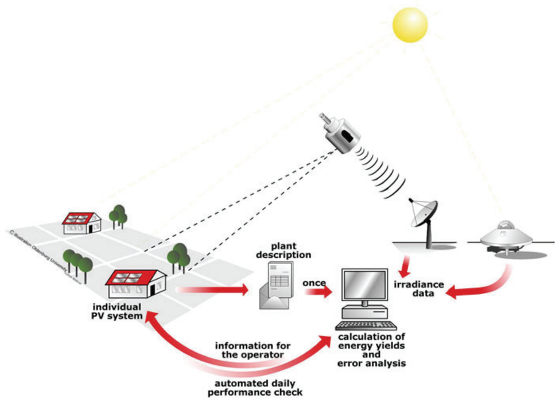

Figure 1: PVSAT-2 routine

2.2 Field test

In the test phase 100 small and mostly privately owned PV systems were monitored between February and October 2005 in Switzerland, Germany and the Netherlands. During the development phase of the procedure, the PVSAT-2 routine was tested with data from well-described and monitored PV systems. During the field test, improvements on the method were introduced directly. The quality and effectiveness of the different steps of the routine was thoroughly analysed.

3 RESULTS

3.1 Importance of correct PV system specifications

For the majority of the monitored PV-systems the PV simulation works well, the accuracy for well-working systems is described in section 3.2.

Initially the simulated hourly energy yield did not correspond well with the measured energy yield for 48 of the PV systems without ‘failures’. This mismatch was caused by different factors, which are shown in Figure 2 and discussed in the following paragraphs.

Errors in installation
- *Undersized cables*

Errors in system descriptions
- *Wrong azimuth orientation given*
- *Wrong installation type given (roof top with large/small spacing, roof integrated, free standing,..)*
- *Incorrect module and inverter specifications*

Figure 2: Causes for simulation mismatch found in the test phase

One cause for a mismatch is an erroneous installation of the PV system, thereby reducing the system efficiency. As example, in the test phase for one of the German systems undersized cables were used, which caused an energy loss of circa 10 %. This was discovered in a detailed study that was triggered by the low yields of this system [5]. Although the owner of the system might not immediately decide to replace these cables, it is useful to know there is an energy and financial loss for this reason.

Errors in the system description turned out to be an important reason for a simulation mismatch. The system description forms were filled out by the owners of the PV systems. As the test users were no PV experts, significant uncertainties in the specification of the tilt angle and azimuth were found. For a quarter of the systems in the test phase the azimuth was wrongly specified. An example of this is shown in Figure 3; the original indicated azimuth of 180 degrees (exactly south) was corrected to 155 degrees (towards south east) on basis of measurements and feed-back from the test user. This effect is quite easily observed, when looking at the hourly measured and simulated energy yield of a clear day, but it is more difficult to correct this automatically because of e.g. clouds and shading effects. An incorrect azimuth has only a minor influence on the daily energy yield. But since hourly energy yields are used for identification of the failure type, the failure detection routine may detect shading, because of a wrongly specified azimuth. This can be seen in Figure 3 in the afternoon hours where the measured yield is significantly lower than the uncorrected simulated energy yield (Psim180) for several hours. After correction the small remaining differences between the measured and simulated energy yield at e.g. 13h00 are covered by the general error margins in the simulated energy yield.

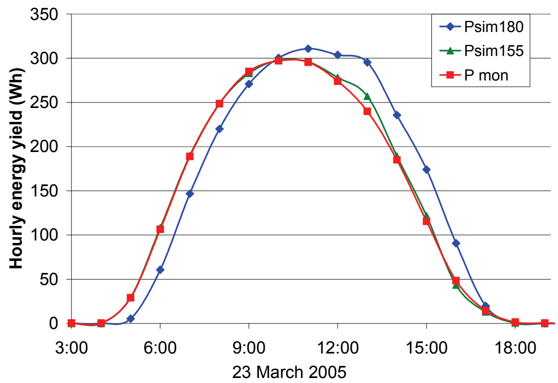

Figure 3: Measured (Pmon) and simulated hourly energy yield before (Psim155) and after (Psim180) correction of azimuth

A wrong description of other input parameters is more difficult to find. A detailed analysis revealed for a German system that the installation type was not ‘small distance from the roof’, but ‘roof integrated’ [5]. Therefore the temperature at higher irradiation values was higher than assumed, resulting in a perceived energy loss of ca. 10 %.

The module and inverter specific information, used for simulation of the energy yield are derived from datasheets. An uncertainty is therefore introduced by not having module specific flash test power; this uncertainty of 5 or 10 % is usually specified in the datasheets. Furthermore especially for older systems (some of the systems in the test phase were installed in 1994) degradation effects could be relevant. Without a detailed investigation it is difficult to quantify the effect of this on individual systems.

For this reasons an initial phase is proposed, before the automatic monitoring process starts. In this phase it would be possible to check the system description and simulation. Possible reasons for energy loss could be identified. Furthermore, module and inverter characteristic parameters could be optimized. This phase would guarantee that the monitoring starts with correct parameter settings and therewith, increase the possibility of a correct detection of possible future failures. Also other options like involving the installation company would help in ensuring a correct system description. For newly installed systems, the above-mentioned problems would play a less important role.

3.2 Accuracy of irradiance data and PV simulation

The failure detection routine is based on the comparison of measured and simulated hourly energy yield; therefore, information on the quality of hourly-simulated energy yield is needed. The uncertainty in the simulated energy yield is dominated by uncertainties in the irradiance values. Within the PVSAT-2 project the data quality of Meteosat-7 and Meteosat-8 have been evaluated for 20 meteorological stations of the German Weather Service for the year 2005. The relative standard errors for hourly, daily and monthly data and the bias are presented in Table 1. The absolute standard error (σ, equation 1) is defined as the standard deviation of the irradiance, which is based on the difference between the satellite value (G_{sat}) and the measured value (G_{meas}). The bias is the systematic error between satellite-derived and measured irradiation for the whole year.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(G_{sat} - G_{meas})^2}{N}} \quad (1)$$

	Met-7	Met-8
Stderr, hourly	19.4	17.5
Stderr, daily	10.7	9.8
Monthly	5.2	4.7
Bias	1.3	-0.5

Table 1: Accuracy of satellite-derived irradiance data (%)

The table shows that the accuracy of the irradiance data has improved with Meteosat 8. It also shows that for failure evaluation it is important to consider longer time intervals, since uncertainties are smaller for daily and monthly time intervals compared to hourly intervals. Furthermore, it is important to note that the accuracy differs per season. The relative errors are much larger in the winter months and therefore it will take a longer time to identify a failure. The absolute errors are smaller than in summer, since also power production is lower. The standard deviation of the PV simulation is dominated by the standard deviation of the satellite-derived irradiance [6].

The previous given standard errors are based on measurement data, which is obviously not available in real use of the PVSAT-2 routine. Therefore, in the PVSAT-2 method situation specific uncertainty margins are provided with the hourly-simulated irradiance, in order to decide if the difference between measured and simulated energy yield is caused by uncertainty in irradiance or by a failure. These situation specific uncertainty margins are based on an extensive empirical weather-dependent error assessment. The uncertainty is dependent on the situation specific sun elevation, cloud cover and variability of cloud cover (how quickly the cloud cover situation changes). For clear sky situations at high sun elevations uncertainties can be as low as 5 % for hourly-simulated irradiance. Under unfavourable weather conditions, like high cloud cover, high variability of clouds, and low sun elevation, uncertainties can be as high as 50 % for a single hourly value.

The shape of the probability density function of the hourly energy yield was found to resemble a Gaussian shape. To cover a 95 % interval of the simulated hourly energy yield, an error margin of two times the uncertainty was used. This means that for an energy loss to be identified as significant in the failure detection routine the difference between measured and simulated energy yield has to be larger than 2σ, i.e. the error margin.

3.3 Example of assigned error margins

The error margins discussed in the previous section depend on weather circumstances and are, therefore, location specific. In this section the error margins are applied to one test system in South Germany for 2005. This will clarify the uncertainty margins present at different time scales. It is important to know how large the energy loss has to be, to be detected by the failure detection routine.

In Figure 4 an overview of hourly error margins is presented. On the *x*-axis the simulated hourly energy yield, normalized by the nominal power of the PV plant is shown; on the *y*-axis the error margin of the simulated energy yield normalized by the nominal power. The blue triangles represent the situation specific error margin for all hourly-simulated energy yield values of 2005. The red crosses show the mean error margin for 2005 relative to the nominal power. The solid diagonal line represents an error margin being equal to the simulated hourly energy yield. The dashed lines represent error margins of 30 and 15 % of the simulated hourly energy yield, for the top and bottom line, respectively. The figure illustrates that the absolute error margins are lower for lower simulated power, but that this is much larger in relative terms. It can be concluded that only for a small part of the measurements (when power production is high due to high irradiation and therefore low error margins because of clear sky conditions exist) failures that produce an energy loss of 15 % and less can be detected. The detectable share increases with a higher hourly energy loss.

In Figure 5 the daily-normalized error margins are shown. The daily error margins are much lower; failures

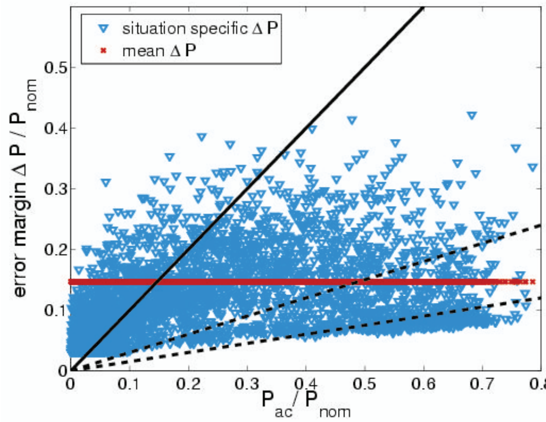

Figure 4: Hourly normalized error margins

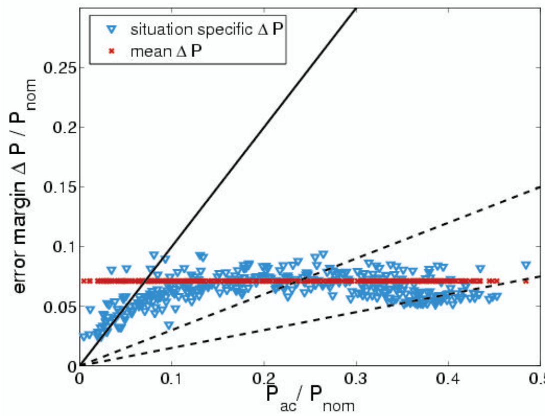

Figure 5: Daily normalized error margins

causing a daily energy loss of 30 % should be detected for days with quite good weather. In Figure 6 the monthly-normalized error margins are presented. Continuous constant failures that cause an energy loss of over 30 % for a whole month can even be detected in winter. In summer, system faults leading to energy losses of circa 15 % can also be detected on a monthly basis. This shows again that it is important to also use longer time intervals for failure detection.

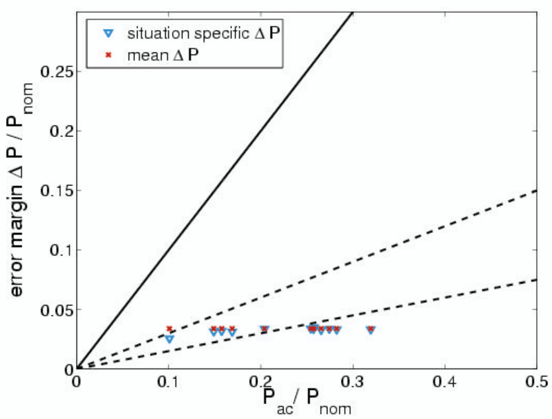

Figure 6: Monthly normalized error margins

3.4 Examples from the test phase

During the field test 100 systems were monitored. The following 'malfunctions' occurred during the test phase: snow, shading, total blackout, power limitation by the inverter and string errors. The detectable failures in the failure detection routine are listed in Table 2 sorted by their general failure type.

General failure type	Failure
Constant energy loss	Degradation
	Soiling
	Module defect
	String defect
Changing energy loss	Shading
	Grid Outage
	High losses at low power
	Power limitation
	MPP tracking
	Hot inverter
	High temperature
Snow cover	Snow cover
Total blackout	Defect inverter
	Defect control devices

Table 2: Detectable failures

The failure detection routine consists of two parts. The failure profiling method checks if there is a significant daily energy loss; if so it sorts the failures in four categories: snow, changing energy loss, constant energy loss and a total blackout. A changing energy loss is for example shading or power limitation of which the energy loss is changing over the day, while a constant energy loss, refers to a defined percentage (with uncertainty) of energy loss caused by e.g. a string error.

The second method, the so-called footprint method, applies a statistical approach for averaging normalized power over three domains: power, time and sun elevation for a one, seven and thirty-day period [3]. Based on this approach the footprint method detects morning or evening shading, permanent power loss and power limitation by the inverter.

One string error detected during the test phase will be discussed as an example. Also general results will be given.

In the Netherlands AC-systems are common, this means the inverter is mounted on the back of the module. 9 of the 29 Dutch test users had an AC system with between 4 and 12 modules and inverters. The described system consists of six AC-modules and inverters (570 Wp). Measurements for this system are available from 20 February to 30 September 2005, with some weeks of missing data, due to a communication problem of the data logger.

One of the inverters broke down in the end of March; another one broke down in the second week of August. Figure 7 presents the simulated and the measured hourly energy yield for 23 March (no failure), 1 April (1 broken inverter) and 16 August (2 broken inverters). It can be seen that the energy loss at 1 April is not significant on an hourly basis, while at 16 August a significant deviation between measurements and simulation is seen at almost every hour. All hourly measured and simulated energy values are shown versus the hourly irradiation in Figure 8. Three lines can be clearly distinguished. From top to bottom they are, respectively, the simulated energy yield, the measured yield with respectively one and two broken inverters. The traces of these errors are equivalent to those of 'string failures' in bigger systems. At high irradiance values the lines are clearly distinguishable and therefore failures can easily be detected. For irradiances lower than 400 Wh/m^2 the different situations cannot be distinguished.

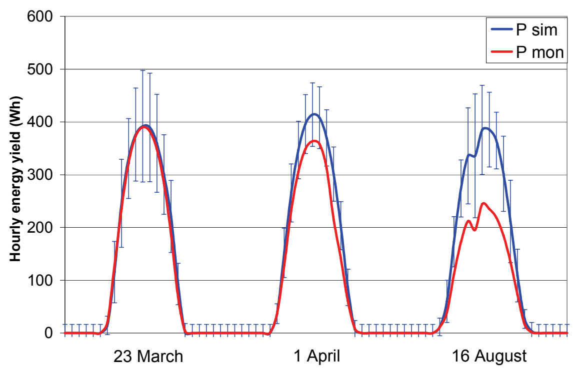

Figure 7: Hourly measured (red) and simulated (blue) energy yield with error margins for a day without a failure (23 March), with one (1 April) and two (16 August) broken inverters

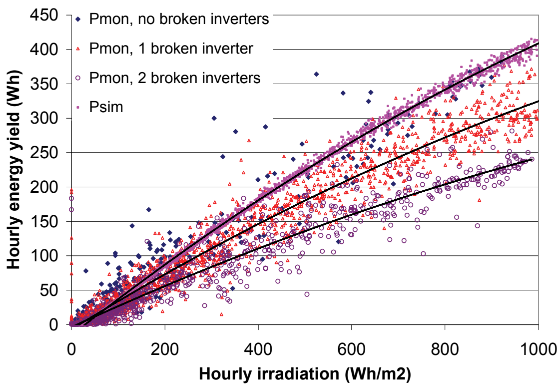

Figure 8: Hourly simulated (Psim) and measured (Pmon) energy yield for total monitored period

Consistent with the results in 3.3, the failure profiling method only detects a constant energy loss when the daily irradiation is very high (~>7000 Wh/m^2) for the period with one broken inverter (17% energy loss). After the second inverter broke down, the frequency of detection of the malfunction increased, since a 33 % energy loss is detected at days with a daily irradiation larger than circa 3000 Wh/m^2.

The footprint method detects a permanent power loss by checking if there are enough intervals on the relative power range with a significant energy loss, for a period of a day, a week, and a month. For the intervals in the higher power range, for example between 70 and 80 percent of nominal power, uncertainties are small. Therefore, an error point is easily found. Since this is not the case for low power categories, it takes some time before a defect inverter is discovered. The averaging approach for 7 and 30 days reduces the uncertainty in the simulation. The footprint detects the permanent power loss from half June onwards.

Also other failures were detected. The footprint method detects shading if there is an hourly significant energy loss, when the sun elevation is lower than 20 degrees, so in the early morning and in the late evening. The failure profiling method detects shading if it causes a significant daily energy loss; in the test phase shading was detected because of some major shading of a tree in mid-day. Intermediate shading (limited energy loss, not in early morning, late evening) is not yet detected. We are looking further into including more options in the footprint for this. Another option is to include shading obstacles in the system descriptions and calculate simulated energy yield including shading.

Furthermore snow was frequently detected for Dutch, German and Swiss systems in winter. Also total power blackouts are detected if the simulated energy yield is larger than 1000 Wh/m^2. Also power limitation was detected for a few systems.

4 CONCLUSIONS

The field test has shown that the detection of failures by the PVSAT-2 routine is strongly dependent on the uncertainty in the satellite-derived irradiance. On clear days in summer the uncertainty is relatively low and failures resulting in a daily energy loss of 15 % can be detected. However in cloudy weather partial malfunctions will take much longer to be detected. Therefore it is important to consider the monthly time scale. Dependent on weather conditions and size and continuity of the failures, it can take between 1 day and several months to detect a failure. The hourly time scale is important for the identification of the specific failure type.

Furthermore, it is very important that the technical system description is correct. It is being considered to introduce an introductory phase.

PVSAT-2 is marketed by Meteocontrol AG, Augsburg Germany under the name safer'Sun Satellite (www.meteocontrol.de) and by Enecolo AG, Mönchaltorf, Switzerland under the name SPYCE (www.spyce.de). More information can also be found at www.pvsat.com.

5 ACKNOWLEDGEMENTS

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