Paper presented at the 17th European Photovoltaic Solar Energy Conference, October 2001, Munich

PVSAT: Remote Performance Check for Grid Connected PV Systems Using Satellite Data, Evaluation of one Year of Field-Testing

JethroBetcke[1], Vincent van Dijk[1],Christian Reise[2], Edo Wiemken[2], Peter Toggweiler[3], Carsten Hoyer[4], Detlev Heineman[4], Horst Dufner[5] Frank Wiezer[6], Hans Georg Beyer[7]

[1] Utrecht University, Copernicus Institute, Department of Science, Technology & Society, Padualaan 14, NL-3584CH Utrecht, The Netherlands, Phone: +31 302537600, Fax: +31 302537601, E-mail: j.w.h.betcke@chem.uu.nl

[2]Fraunhofer Institute for Solar Energy Systems ISE, [3]Enecolo AG,

[4]University of Oldenburg, Department of Energy and Semi-conductor Research

[5]Deutscher Fachverband Solarenergie e.V, [6] Organisatie voor Duurzame Energie, Technical University, [7]Department of Technical Engineering, [7]University of Applied Sciences Magdeburg-Stendal

ABSTRACT: The PVSAT procedure provides users of grid-connected PV systems with an individual monthly reference yield. Comparison of this reference yield with measured yield can identify system faults. This paper describes the one-year field test of the PVSAT procedure. The field test was used to test and improve the PVSAT software and organisation; to determine the differences between measured and reference yield under field conditions; to establish the causes of these differences and to determine when a system operator or system supplier should be warned about a possible malfunction within in the system. During the one-year test phase 69 owners of PV-systems in Austria, Germany, the Netherlands and Switzerland reported their measured monthly yield and received a reference yield. The field test enabled us to identify and solve problems in the procedure. Throughout the year the normalised difference between measured and reference yield remained within a band throughout the year, but some outliers occur. An analysis of the data showed that the differences between measured and reference yields could be partially explained by system faults, nearby shading, inaccurate horizon description, inaccurate specifications of components and insufficient accuracy of the PVSAT irradiation model (during one or two months in the year). The results were, where possible, corrected for external effects. This gave a first estimate of the accuracy of the PVSAT procedure under field conditions of 15 to 20 kWh/kWp. This accuracy can be improved if the system installer describes the PV system and surroundings, the true peak power of modules is included in module specifications and a model for the shading of nearby objects is included in the PVSAT model.

Keywords: Performance-1: Monitoring-2: Grid-Connected-3

1. INTRODUCTION

Due to the fluctuating yield of photovoltaic (PV) systems, partial systems faults or decreasing performance are difficult to recognise for PV system operators who are not PV specialists. The PVSAT procedure [1] provides users of grid-connected PV systems with an individual monthly reference yield. This reference yield is determined by an INSEL simulation that uses irradiation determined from satellite images and the individual system configuration as input. The users of PV systems can compare the reference and actual yield to assess the performance of their system. The development of the procedure and test on historic data are reported in [2].

In addition to the test on historic data the owners of PV-systems in four countries have tested the PVSAT procedure in practice during the period of May 2000 to June 2001. This paper reports about this field test. The goals of this field test are:

1) to test and improve the PVSAT software and procedure.
2) to determine the differences between the yields measured under field conditions and the calculated reference yields .
3) to establish the causes of differences between yields determined with the PVSAT procedure and measured yield.
4) to determine when a system operator or system supplier should be warned about a possible malfunction within in the system.

In the sections below we will report about the set-up of the field test, the practical experiences during the test, the differences found between measured and reference yield, the causes of these differences. Also we will make a first estimate of the accuracy of the PVSAT method under field conditions. In the discussion we will compare the results found here with the results found in the test on historic data. Finally we will draw conclusions about the objectives stated above and make recommendations for improvement of the PVSAT procedure.

The field test results are reported in full detail in [3].

2. SET-UP OF THE FIELD TEST

2.1 Test clients

Sixty-nine test clients in Austria, Germany, the Netherlands and Switzerland owning 72 systems participated in this field test. Table I shows that a variety of system types and sizes were represented.

Table I: Categorisation of the systems by the type and size of their inverter (several identical inverters may be included in one system)

Inverter type / Country	AC-module	String inv.	de-central ≤2.5 kW	de-central 2.5 kW to 5 kW	de-central 5kW to 10 kW	central >10 kW
Nether-lands	22	3	5	1	-	-
Germany/ Austria	-	19	8	2	3	-
Switzer-land	-	-	-	4	-	5

Before the field test, the test-clients filled in a questionnaire regarding their systems. The questionnaire contained questions about the components in the systems, the kWh meter and the obstacles as seen by the PV array

Most clients measured the yield of their system with a class I kWh meter [4]. Some German clients measured the yield with the built-in equipment of the inverter. The clients reported the measured yield at the end of each month. At the same time they received the PVSAT reference yield.

The field test ran from May 2000 to May 2001.

2.2 Set-up of calculation and software

A central server at Oldenburg University calculates the monthly PVSAT reference yields for individual systems from an irradiation time-series and the description of the individual system. The irradiation time series is specific for the location of an individual system and is determined from METEOSAT images [2].

The PVSAT operator in each country can upload system descriptions to the PVSAT server and order yield calculations for periods of a day or longer. The operator communicates with the server via e-mail. These can be typed by hand, or can be generated by means an MS-Access application developed by Enecolo AG.

The MS-Access application serves both as an interface to the Oldenburg server and as a database that holds system and component descriptions. A large amount of component descriptions are stored in the database as a standard. The user can also define new components. Furthermore, the Access application can directly send e-mails and faxes with PVSAT results to the end users or print postcards with these results.

3. PRACTICAL EXPERIENCES DURING THE FIELD TEST

In general the input necessary for the PVSAT system model were available. For some older systems the component specifications were difficult to obtain. In one case the system configuration was too complex for the PVSAT model and simplifications had to be made in the system description.

After some initial problems with software and the reception of satellite were solved it was possible to deliver the PVSAT reference yield to the test clients within a few working days.

The PVSAT MS-Access application showed to be user friendly, but some insight in PV-systems is necessary to manage it. This is especially true for entering non-standard systems.

4. DIFFERENCES BETWEEN MEASURED AND PVSAT REFERENCE YIELD

4.1 Indicator

A PV system owner needs to know when the difference between the measured yield and reference yield becomes significant and the installer or maintenance contractor should be warned to check the system. Preferably we would like to express the difference in such a way that the threshold value is constant throughout the year.

In [2] it has been shown that the relative difference between measured and reference yield can become very large in months with low irradiation. This is also found in this field test [3]. We therefore chose to express the difference between measured and reference yields as the difference between measured and reference yield normalised to the nominal power of the system i.e.:

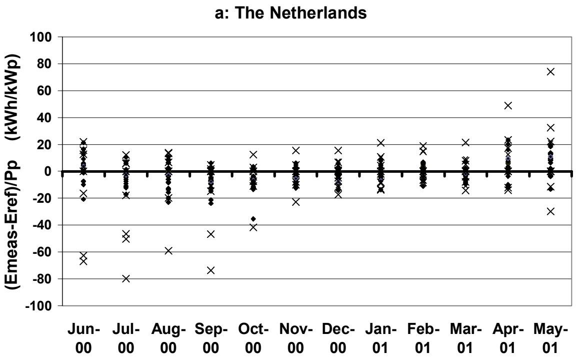
$$\Delta E_{norm} = \frac{E_{measured} - E_{calculated}}{P_{installed}} \qquad (1)$$

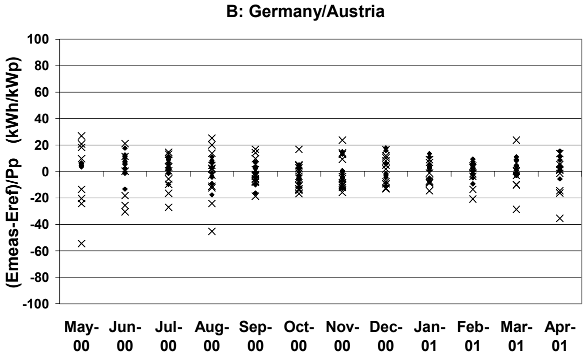
As will be seen in the next subsection the value of ΔE_{norm} remains within boundaries that are more constant through the year. Another reason to choose this indicator is that owners of PV systems will be interested in maximising the annual energy yield of their system. This indicator expresses this.

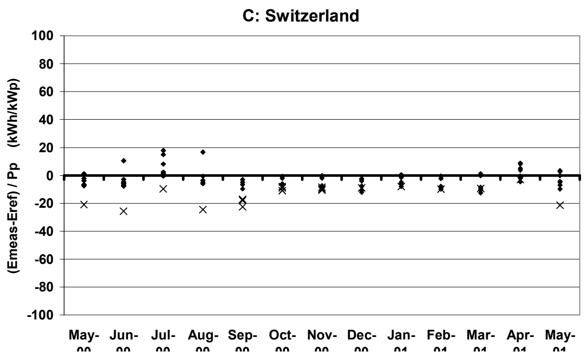
Based on the results found in [2] we would expect that ΔE_{norm} remains in a bandwidth of $\pm$ 10 kWh/kWp per month. For a well performing system a threshold value of 10 kWh/kWp is equivalent with roughly 10% of the average monthly yield during the period March to October

4.2 Results

Figures 1 a to c show the monthly values of ΔE_{norm} for the months in the field test. It should be noted that these results







still include data points corresponding with system faults, inaccurate system descriptions etc. The results differ slightly for the three data-sets.

For most systems in the Dutch data-set the normalised difference remains within a $\pm$ 20 kWh/kWp bandwidth. However some outliers occur and the deviations are larger in May and June. The same is true for the German/Austrian data set, however the larger deviations occur during April and May.

Except for July and April, the majority of the Swiss results remain within a band of -10 to 0 kWh/kWp, with only negative valued outliers. The bandwidth of these results is much smaller than for the other two data sets. Furthermore, there is a clear offset of ca. -5 kWh/kWp i.e. there is a systematic overestimation of the results

These results do not give enough information about the accuracy of the PVSAT procedure since these results still include data points corresponding with system faults, inaccurate system descriptions etc. We will discuss this in the next section.

5. ANALYSIS OF RESULTS

5.1 Causes of differences between measured yield and reference yield.

The differences between measured yields and PVSAT reference yields can have several causes, which are categorised below:

- *Uncertainty in the model used by PVSAT*
  This can be both the irradiation model as the system model.
- *Uncertainty in the PVSAT procedure not due to the model*
  These are the uncertainty in product specifications and the uncertainty in the yield measurements. Especially the uncertainty in module peak power can be large. Module manufacturers often allow for 10% deviation in their specifations.
- *Uncertainty through inaccuracies of the test clients*
  Especially the description of shading obstacles is likely to be inaccurate. One might argue that these inaccuracies are also a part of the procedure, however they can be reduced if the installer describes the systems.
- *System faults*
  This is what we want to detect with the PVSAT procedure.

The best way to identify all causes of differences between measured yield and reference yield would be to visit each of the test systems, measure the peak power of the modules, check if the user questionnaire was filled in correctly and check for systems faults. However that approach was not possible within the budget of the PVSAT project. As an alternative we analysed the results in other ways which are discussed below. From this analysis we found the following causes of differences between measured and calculated yield:

Inaccuracy of the irradiation model

We compared the monthly horizontal global irradiation calculated by PVSAT with the monthly horizontal global irradiation reported by a meteorological station in the Netherlands and a meteorological station in Switzerland. For the interpretation of the results it is helpful to know that an irradiation of 1 kWh/m^2 is roughly equivalent with a system yield of 1 kWh/kWp.

For the Netherlands the comparison showed an underestimation of the irradiation of 10 to 12 kWh/m^2 in the months May and June. The rest of the year the difference remained within a band of $\pm$ 6 kWh/ m^2. This is consistent with the results found in figure 1a. In [2] it is reported that the lesser accuracy is due to the presence of broken cloud fields in these months. In the near future this problem can be partially solved with the launch of a new satellite, Meteosat Second Generation, that will offer a higher spatial resolution than the current satellite

For Switzerland the comparison showed an overestimation of the irradiation of ca 5 kWh/m^2 for nine months a year. This is consistent with the results found in Figure 1b.

Mutual shading of modules in a flat roof system

For two AC-module systems on a flat roof the yields of the separate modules were available. The annual yield of the first row was ca 5% higher than the yields of the rows behind it. This shows that the effect of nearby shading can not be neglected.

In the current version of the PVSAT system model shading of nearby objects is not included, since this is more complex than shading due to the far horizon. However, for flat roof systems in a row configuration an empirical correction factor without adding complexity to the model.

PVSAT system model

To save calculation time the PVSAT system model contains some simplifications that might make the model less accurate for some specific system or component types. However, a wide variety of system and component types can be found among the systems with a good agreement between measured and reference yield. We therefore expect that this effect is negligible compared to other effects.

Overestimation of horizon

In ten cases the predicted yield was below average while the measured yield was not. Furthermore, for these systems the predicted array plane irradiation was below average, while the predicted horizontal global irradiation was not. This is a clear indication of overestimation of the height of obstacles. For future application of the PVSAT procedure it is therefor recommendable to determine the height of the obstacles in a more reliable manner, for example by means of photography.

Inaccuracies of measurement equipment

The accuracy of a class I kWh-meter is 1% at the full range of the scale. For lower yields the uncertainty may be higher. Overall we expect this effect to be negligible compared to other effects.

For one German system the yield was measured with both the inverter as with a separate kWh-meter these showed a systematic difference of ca 5%. We therefor recommend not to use inverter measuring equipment.

Inaccurate reading of measurement

In three cases yields were reported that were far above average. We expect that for these values the measurement period was longer than reported.

Time of measurement
In general user's read out the yield of their system in the early morning or in the evening. In a limited number of occasions users read out the yield of their systems during the day. The smallest time span allowed by the current PVSAT software is one day. If the measurement is taken at solar noon we would expect an error of ca 1.5% (1/60). Furthermore this error is compensated in the next month's reading.

Inaccurate specification of module peak power
The difference between the true peak power of a module and the nominal power can be considerably. Many producers specify an uncertainty of 10%. For two German systems the true peak power of the modules was known from earlier analytical monitoring. Differences up to 10% between nominal peak power and actual peak power were found. We expect that this effect will also play a role for other systems.

System faults
Defects were reported by the owners of seven systems. In most cases these were defects of the inverter. For other systems defects were likely because the measured yield was far below average, while the reference yield was not.

5.2 Estimation of accuracy of the PVSAT procedure
To estimate the accuracy of the PVSAT model under field conditions the data set should be corrected for external causes of differences between measured yield and reference yield. Since our knowledge of theses causes is incomplete we could only remove the data-points which we expected to correspond with error causes outside the PVSAT procedure. The removed data points are marked by 'X' in Figure 1.

After the clean up of the data set most outliers in Figure 1 a to c are removed, and the bandwidth has become smaller. From these results we estimate the uncertainty of the monthly reference yield under the conditions of this field test to be $\pm$ 15 kWh/kWp for Germany, Austria and Switzerland and $\pm$ 20 kWh/kWp for the Netherlands.

Analysis of individual systems shows that for all systems of the cleaned data-set ΔE_{norm} remains in $\pm$ 10 kWh/kWp for at least nine months a year.

We recommend that an owner warns the maintenance contractor when $|\Delta E_{norm}|$ is larger than 20 kWh/kWp for a single month or larger than 10 kWh/kWp for more than three months a year.

6. DISCUSSION

In [2] the PVSAT model was validated on two well described systems. There it was found that the normalised difference between the monthly measured yield and the monthly reference yield remained within a ban of $\pm$ 10 kWh/kWp. The uncertainty found in sub-section 5.2 is a factor 1.5 to 2 larger.

We cleaned our data-set for inaccurate descriptions of system, components and horizon, known system defects and measurement errors with the data available to us. However the absence of site-visits makes it impossible to correct the data-set completely. Therefor we expect a higher accuracy when all these effects are taken into account.

Other causes of the found difference in accuracy could be the wider geographical distribution and wider variety of the systems in the field test compared to the test on historic data.

7. CONCLUSIONS

- The field test of the PVSAT procedure has shown that it is possible to deliver a reference yield value to PVSAT clients within a few working days after the end of the month.
- System faults, nearby shading, inaccurate horizon description, inaccurate specifications of components and insufficient accuracy of the PVSAT irradiation model (during one or two months in the year) are causes of differences between measured yields and PVSAT reference yields.
- The accuracy of the procedure can best be expressed as the nominal energy yield normalised towards the nominal system power (kWh/kWp). A PV system owner should warn the maintenance contractor when the normalised difference between measured and reference yield is larger than 20 kWh/kWp for a single month or larger than 10 kWh/kWp for more than three months a year.
- A lower threshold valuefor ΔE_{norm} can be set if:
  - the system configuration is described by the system installers
  - the horizon line is determined objectively, for example by photography
  - module specifications included the real peak power.
- A simple empirical correction for row-shading could improve the accuracy of PVSAT for flat roof systems

ACKNOWLEDGEMENTS

This work was supported financially by the EU Joule program (JOR3-CT98-0230). Erik Alsema and Wim Turkenburg are thanked for valuable comments. Last , but not least, we would we like to thank the PV system owners who participated in this field test.

REFERENCES

[1] C. Reise, E..Wiemken, P. Toggweiler, V. van Dijk, D. Heineman, Proceedings 16th European Photovoltaic Solar Energy Conference, James & James (2000), 2618.
[2] H.G. Beyer, D. Heinemann & C. Hoyer, C. Reise, E. Wiemken, Elsewhere in these proceedings (2001).
[3] J.W.H. Betcke, V.A.P. van Dijk, E. Wiemken, P. Toggweiler, C. Hoyer, report NWS-E-2001-27, Department of Science Technology and Society, Universiteit Utrecht, Utrecht (2001)
[4] IEC, report 61036, IEC, Geneve, (2000).