IRRADIANCE MAPS APPLIED FOR THE PERFORMANCE ASSESSMENT OF PV SYSTEMS - A CASE STUDY FOR THE GERMAN FEDERAL STATE OF SAXONY

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ABSTRACT: For the estimation of the expected annual energy yield and the month by month check of a PV system's performance, methods based on irradiance maps published by weather services, both general or dedicated to solar energy application, are in use. Examples for these types of information for Germany are the annual and monthly radiation maps as published by the German Weather Service DWD or the data bank of hourly irradiance data with continuous spatial coverage prepared by the University of Oldenburg.
To assess the validity of these data sets for the aforementioned tasks, a case study for a region covering the German federal state of Saxony is performed using data for the year 2005. For this region sets of measured irradiance data from stations operated by the German Weather Service and a state-owned agro-meteorological network are available. An assessment of the end use accuracy of the irradiance data is done by a set of monthly energy yield data of grid connected PV systems. The comparison of information on radiation sums is on one hand performed by the monthly analysis of the bias and the RMS-error for the data bank versus the ground station data. For an additional inter-comparison of the different data sources, the annual maps presenting the estimations of the irradiance sums for 2005 are analyzed, giving information of data accuracy with respect of the spatial structure of the irradiance field. The assessment of the end use accuracy of the data is - for the data generated in Oldenburg - done via the estimation of the system yield using a system simulation as developed within the PVSAT-2 project.

Keywords: PV system, solar radiation, monitoring

1 INTRODUCTION

Due to the favorable conditions for PV applications in Germany given by a guaranteed feed-in tariff, carefully prepared and controlled PV projects offer the opportunity of an economically valuable outcome. A prerequisite for the continuous performance check is an exact knowledge of the site specific meteorological conditions (irradiance and temperature) for the operation of the PV generator.

This calls for data sources which offer an almost continuous spatial coverage and stretch over several years. These conditions are fulfilled by data sets derived as irradiance maps from the images taken by geostationary satellites, for Europe by the Meteosat satellites.

Crucial for this task is the accuracy of the irradiance information. The present paper is directed to the validation of a number of data sources that are in application in Germany. As region of inspection, the German federal state of Saxony is selected here; the evaluation period is the year 2005. The investigation focuses on both, the accuracy of the estimated irradiance data itself and their accuracy in view of their use, the energy yield estimation for PV systems.

Concerning the irradiance data, the estimated values are compared to 'ground truth' as presented by hourly data of the global horizontal irradiance from the DWD network, monthly sums from the agro-meteorological measuring network of Saxony [1], and some on-site data of irradiance on the inclined surfaces of PV generators.

For the check of the estimation of yield of PV systems, modeled data are compared to measurements at 10 systems in Saxony.

Based on these comparisons the attempt for a general conclusion on the currently achievable quality of estimates of irradiance conditions and performance of PV system will be made.

2 SOLAR RADIATION DATA

In this section, the basic accuracy of different sources for irradiance and radiation data in the investigated region of Saxony is analyzed.

2.1 Description of the maps with solar radiation data used

The following maps of hourly irradiances and annual radiation sums (global horizontal data) were available:

- hourly irradiance maps prepared by the Heliosat scheme applied to images from the Meteosat-7 satellite (Meteosat First Generation MFG, spatial resolution: 3x5km), processed as described in [2],
  and the Meteosat-8 satellite (Meteosat Second Generation MSG, spatial resolution: 1.25x1.75km) processed as described in [3,4], including an enhanced snow cover detection
- a map of the annual radiation sum as routinely prepared by the DWD [5]
- a map of the annual radiation sum provided by the Climate Monitoring Satellite Application Facility (CM-SAF) prepared from Meteosat-8 and NOAA/AVHRR satellite data [6]

In addition, for the Heliosat-derived data a post-processing is applied to calculate the irradiances on inclined (generator) surfaces. This procedure follows the approach as used in the PVSAT-2 project (see e.g. [7],[8]).

2.2 The ground data

Within the region of Saxony (se fig.1), hourly data from the three DWD stations 'Dresden', 'Chemnitz', and 'Zinnwald' are available. In addition, monthly data from 13 stations of the agro-meteorological measuring net of Saxony are under inspection. Data of irradiance on inclined surfaces are available from on site measurements at two PV systems. The locations of these stations and systems are mapped in fig. 1.

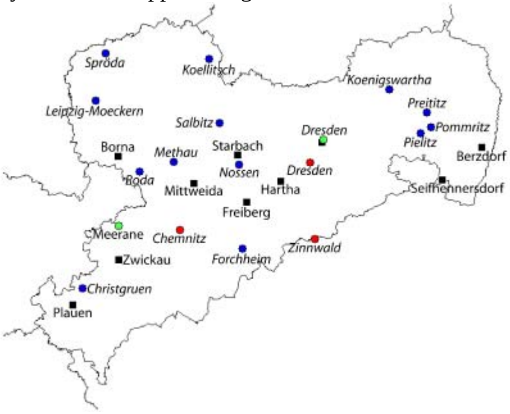

Fig.1: Map of the German Federal State of Saxony. Indicated by circles are the sites of meteorological stations that are operated by the German Weather Service DWD (red) and the agro-meteorological service of Saxony (blue) and two sites with irradiance measurements in-plane of PV systems (green). The black squares give the locations of PV systems analyzed in this study.

2.3 Validation results

2.3.1 Hourly data

Form the two Heliosat products hourly irradiance information is available. These model data are analyzed with respect of their deviations to the hourly irradiance data for the 3 DWD stations. Skipping all data sets with gaps in either, the ground or the satellite data, the annual and monthly relative mean bias errors rMBE and the relative root mean square errors rRMSE are extracted, both normalized by the respective ground data.

The figures 2a-2c give for the three stations the annual trace of the monthy rMBE and rRMSE for the Heliosat/Meteosat-8 data.

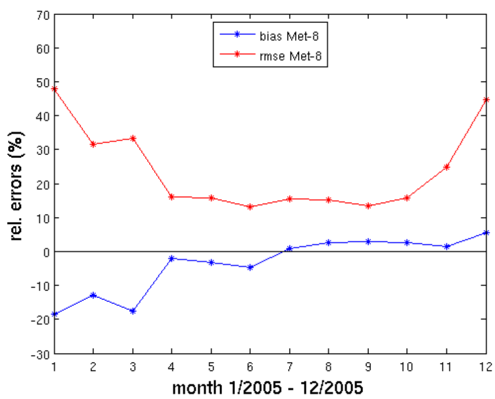

Fig. 2a: Monthly values of the relative mean bias (blue) and the relative root mean square error of the modeled global irradiance (model: Heliosat/Meteosat8) for the DWD station at Chemnitz.

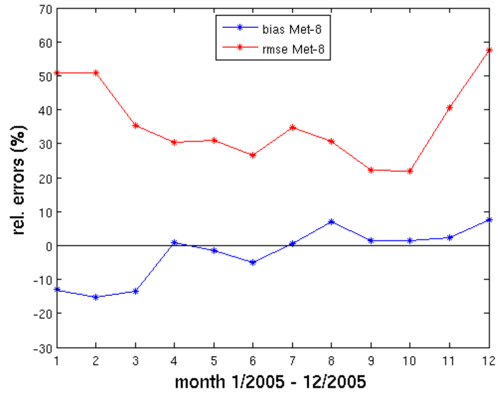

Fig. 2b: Same as figure 2a for the station at Dresden.

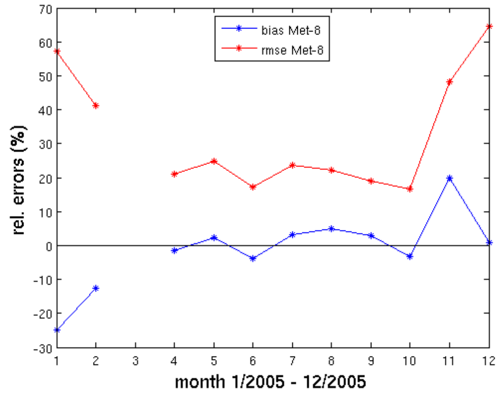

Fig. 2c: Same as figure 2a for the station at Zinnwald. Ground data are missing for the month of March.

It can be stated, that the model errors are a clear function of season, being elevated in the winter/spring months. For the summer months – giving the highest contribution to the annual irradiance sums - the biases are mostly well below 5%. The RMSE stays at around 20% due to the problem of the space/time match of satellite and ground data.

This is analyzed in the figures 3 and 4 giving the scatter plot of hourly irradiance data form ground and satellite for one location and month. The symmetric appearance of the data around the identity line is an indicator of a small bias. Figure 4 gives the result of the test of the modeled distribution function. Shown is the comparison of a presentation of the cumulative distribution of ground and satellite data, which show an almost perfect match. Thus, it may be concluded, that not only the irradiance sum, but also the probability of occurrence of different irradiance levels is described well by the model.

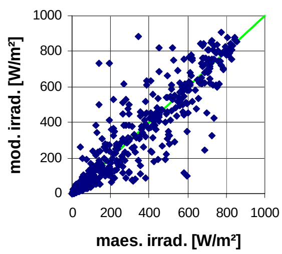

Fig. 3: Scatter diagram of the measured and modeled hourly irradiances for the station of Dresden, July 2005. The model data stem from the Heliosat/Meteosat-8 combination.

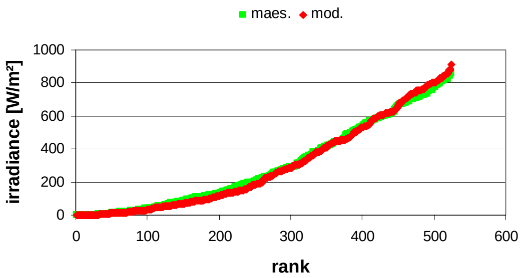

Fig. 4: Cumulative distribution of measured (green) and modeled irradiance data (same data set as fig. 3) presented here as plot of the irradiance values sorted by magnitude.

At two PV systems, the irradiance on the inclined PV plane is measured. For a system at Meerane (incl. 30° facing south) data cover the whole year, for a system at Dresden (incl. 36°, oriented 4° eastward of the south, location not identical with the DWD Station Dresden in the same city) data only for the months July to November are available.

For Meerane the measured irradiance sum for the months February-December (January missing in the model data) is 1193 W/m². The modeled data give this value with an error of -1.2%. For the Dresden site, the irradiance sum for July to November is 549 W/m². Here the error of the modeled data is +6.5%. The comparison of the values for the monthly radiation sums is given in fig. 5.Thus, from these examples it may be concluded that the additional modeling step given by the transfer of horizontal irradiances to irradiances on the tiled plane do not add remarkable errors to the final irradiance product.

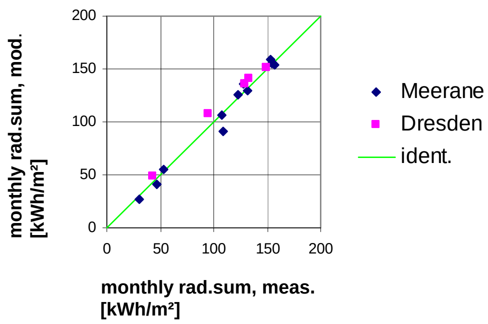

Fig. 5: Scatter plot for modeled and measured monthly radiation sums on the tilted plane for two PV systems. Annual rMBE are -1.2% for the system Meerane and to +6.5% for the system Dresden (July to November only).

2.3.2 Annual data

Analyzing all existing pairs of ground and satellite derived values, the bias of the resulting annul radiation sum from the two Heliosat products can be determined.

Table 1 gives the result. The rMBE for Heliosat/Meteosat8 is less than 3%; the values for Heliosat/Meteosat7 are slightly larger.

	Chemnitz	Zinnwald	Dresden
Measured radiation sum;	1130 kWh/m²	1013 kWh/m²	1101 kWh/m²
Heliosat/ Meteosat 7	rMBE -4.0%	rMBE -4.1%	rMBE -3.1%
Heliosat/ Meteosat 8	rMBE -2.6%	rMBE 0.2%	rMBE -1.6%

Tab. 1: Measured irradiance sums for the year 2005 at 3 DWD stations in Saxony and the rMBE of the two Heliosat schemes. The sums are derived from hours with data in both, measured and modelled sets.

For the DWD and the CM-SAF procedures annual irradiance maps are available only. Due to the incomplete ground data sets the figures for these products cannot directly be compared to the ground based radiation sums. Thus, table 2 gives the comparison of values for the satellite products only.

Rad.sum [kWh/m²]/ Model	Chemnitz	Zinnwald	Dresden
H/M8	1104	1109	1121
H/M7	1106	1113	1121
DWD	1131	1145	1130
CM-SAF	1121	1141	1091

Tab. 2: Annual irradiance sum (complete year) for the 3 sites inspected in detail as given by maps from the models investigated. The mutual differences are in within +/- 3.5%.

It may be remarked that the pairs formed by the two Heliosat procedures and the DWD and CM-SAF perform in parallel with a deviation of about 2-3 percent – lower values attributed to the Heliosat procedures.

Another check of the model data may be performed using the data of the stations of the agro-meteorological network. Due to lower accuracy of that data set - an uncertainty of ~5% has to be assumed - this test should give qualitative information only. Fig. 6 gives the relative deviation of annual sums for the different models from those the network data. The values range from -2 to ~10%. Best model in this case is the Heliosat/Meteosat-7 combination.

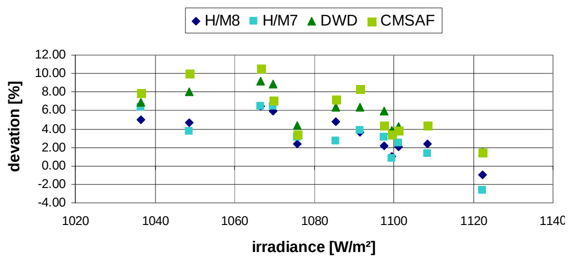

Fig. 6: Deviations of modeled and measured annual irradiance sums for the stations of the agro-meteorological network in Saxony (see fig.1). Shown are the relative errors for the different stations sorted by their measured radiation sum.

It may be remarked, that the pattern of the deviations is similar for all sets of modeled data. This is an indication that differences of the model data are mostly due to a relative offset and only to lesser extend caused by differences in the fine scale of the underlying radiation maps.

This finding is supported by an inter-comparison of annual maps produced by the different sources. As an example for such a map, the one produced by the Heliosat /Meteosat8 combination is given in fig.7.

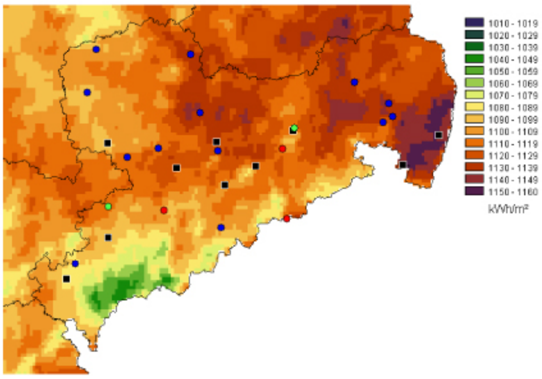

Fig. 7: Map of the annual radiation sum produced by the Heliosat/Meteosat8 combination. The 15 color-coded classes range from 1010 to 1160kWh/m² in steps of 10kWh/m^2.

Fig. 8 shoes the deviation of the annual irradiance sums from this map from those of the DWD map. The deviations range from -62 to 26kWh/m². The standard deviation of the values in this map of differences is 13kWh/m² only, indicating that the errors are quite homogeneous.

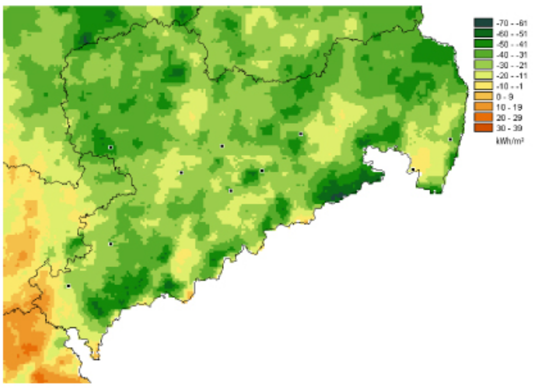

Fig. 8: Map of the differences of the estimates of the radiation sums presented by the Heliosat/Meteosat8 and the DWD map. The deviations are in the range of -62 to 26 kWh/m². The mean deviation of the two maps is -25kWh/m² or ~-2.2% of the annual sum.

The result from all mutual comparisons is given in table 3. With the exception of the parings with the CM-SAF map, the differences in the mean annual radiation sum are limited to 3%. The small changes to the root mean square deviation of the maps to the absolute mean difference indicate that the maps differ mostly by various offsets. The spatial information of all maps is quite similar, which is to be expected as all maps are based on the similar satellite derived information.

Maps intercompared	Mean difference [%]	Root mean square difference [%]
H/M7 - H/M8	-0.4	1.2
DWD - H/M8	2.2	2.5
CMSAF-H/M8	2.8	3.4
DWD - H/M7	2.7	3.0
CMSAF-H/M7	3.2	3.8
CMSAF-DWD	0.5	1.7

Tab. 3: Mean and root mean square differences of the annual radiation sums given by pairs of radiation maps.

3 ENERGY PRODUCTION

3.1 The inspected systems

The yield of 10 systems could be analyzed. The systems have been selected for their high specific energy yield (> 900 kWh/kW), indicating a mostly faultless operation. The locations of these systems are mapped in figure 1. Their installed capacities range from 0.96 to 92 kW. The orientations range from exactly south to +/- 40° east/west with slopes from 25 to 43°. Both rooftop and free standing installations are included.

3.2 The modeling scheme

The system output is modeled according to the PVSAT-2 scheme ([7], [8]). Information on the characteristics of the PV modules and inverters used are extracted from data sheet information. Irradiance data of the Heliosat/Meteosat8 model are used as input.

3.3 Results

The deviations of the modeled monthly and measured annual yields are analyzed giving the rMBE. For systems and months with information on the daily energy gain more detailed analyses are performed.

Table 4 gives the monthly and annual deviations of the specific energy yield for the systems inspected. Whereas the relative monthly deviations may reach quite remarkable values, especially for the winter months, the relative errors for the monthly yield are generally with in -9% and +8%. The average yield is reflected with an rMBE of -1% only.

Location	modeled yield [kWh/kW]	measured yield [kWh/kW]	rel. error [%]
Borna	928	998	-7.0
Seifhennersdorf	926	930	-0.4
Starbach	942	930	1.3
Hartha	976	957	1.9
Zwickau	906	957	-5.3
Plauen	921	850	8.4
Bertzdorf	1040	964	7.9
Freiberg	906	977	-7.3
Mittweida	912	958	-4.7
Dresden	966	989	-2.3

Tab. 4: Modeled and measured annual yield of the 10 systems under inspection.

Figure 9a-9b give examples of the annual course of monthly yield given by data and model.

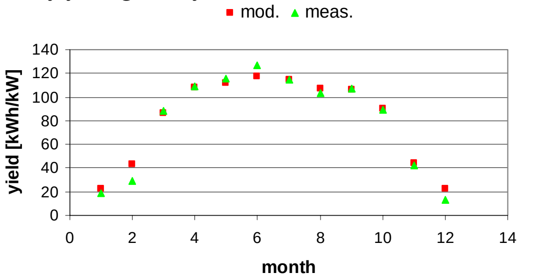

Fig. 9a: Monthly yield figures for a PV System located at Hartha (see tab. 3) as given by measurements and by a simulation based on Heliosat/Meteosat-8 radiation data. The annual rMBE is -2%.

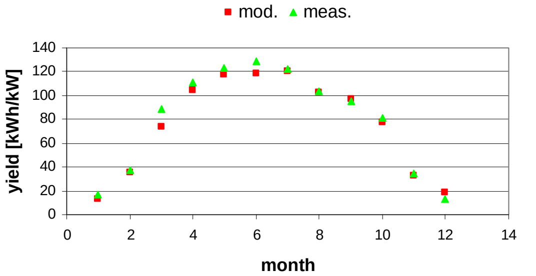

Fig. 9b: Same as fig 9a for a system at Mittweida (see tab. 3). The annual rMBE is -5%.

The achievable quality of this simulation scheme can also be expressed by the example of the analyses of the history of the monthly energy gain for the system 'Hartha'. Figure 10 shows the accumulated yield for the month of May and September (measured data are available with a daily resolution). The curves for the modeled and measured values coincide almost perfectly, i.e. there are no crucial modeling problems on the daily time scale.

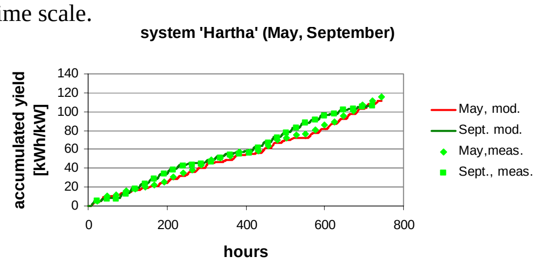

Fig. 10: Trace of the accumulated yields for the system at Hartha for the months of May and September. Given are the curves for the measured (points) and the modeled (lines) data.

4 SUMMARY AND CONCLUSIONS

The study has shown that, using state of the art procedures, it is possible to assess annual radiation sums with relative mean bias errors below 3% from satellite data. The application of different procedures results in mutual differences in the same order of magnitude.

For a further ranking of the procedures and investigations into a reduction of the uncertainties, additional tests involving a higher number of independent high quality ground measurements are needed.

With the current products – assessed in detail here: the Heliosat method applied to Meteosat8 images – the satellite derived irradiance data can be used to model the annual yield of grid-connected PV-system for the actual year within errors margins of +/- 9%.

Taking into account the combined statistics of modeling errors and uncertainties in the systems specification, the lumped yield of an ensemble of systems may be modeled with higher accuracy (for the ensemble under investigation this value is down to 1%).

This information on the basic uncertainty of the yield modeling has to be taken into account when doing estimates of the expected long-term yield of PV systems. It is the starting point for the estimation of the long term uncertainty, adding to the uncertainties due to the inter-annual variability of the radiation resource (see e.g. [9]).

ACKNOWLEDGEMENTS

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