SOLAR IRRADIANCE FORECASTING FOR THE MANAGEMENT OF SOLAR ENERGY SYSTEMS

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ABSTRACT

Solar energy is expected to contribute major shares of the future global energy supply. Due to its fluctuating nature an efficient use will require reliable forecast information of its availability in various time and spatial scales depending on the application. The current status of forecasting solar irradiance for energy generation purposes is briefly reviewed with respect to very short-term forecasting (up to a few hours) and forecasts for up to two days mainly for use in utility applications.

1. INTRODUCTION

One of the major challenges for future global energy supply will be the large scale integration of renewable energy sources into existing energy supply structures. This not only demands substantial efforts in further development of advanced technologies but also makes the availability of precise information on the fluctuating wind and solar resources an indispensable necessity. Any efficient implementation of wind and solar energy conversion processes has to account for this behaviour in respective operating strategies. A key issue hereby is the prediction of renewable energy fluxes, typically for time scales from the sub-hourly range up to two days depending on the given application. Examples are the storage management in stand-alone photovoltaic or wind energy systems, control systems in buildings, control of solar thermal power plants and the management of electricity grids with high penetration rates from renewable sources.

First attempts in irradiance forecasting have been presented more than twenty years ago (Jensenius and Cotton, 1981), when daily solar radiation forecasts for one to two days in advance have been produced with the Model Output Statistics (MOS) technique (Glahn and Lowry, 1972). Subsequent years showed only minor attempts or progress with respect to the development of solar irradiance forecasting methods. Heck and Takle (1987) and Jensenius (1989) both presented variations of the MOS approach without introducing new elements.

This paper presents different state-of-the-art approaches to solar irradiance forecasting in different time scales. Very short-term forecasting in a temporal range of 30 minutes to 6 hours (section 2) is based on the analysis of satellite data. Forecasts for up to 2 days ahead (section 3) are based on numerical weather prediction. The time scale - and its corresponding spatial scale - is governed by the application and its time constants. For example, an operation of a PV-diesel system needs information in the very short time range, whereas an integration of solar power into electricity grids will largely benefit from forecasts one or more days ahead. The latter is also the time range where the output from numerical weather forecasts is applied.

2. VERY SHORT-TERM FORECASTING

As far as short-term horizons are concerned, satellite data are a high quality source for irradiance information because of its excellent temporal and spatial resolution. Due to the strong impact of cloudiness on surface solar irradiance, an accurate description of the temporal development of the cloud situation is essential for irradiance forecasting.

For short-term time scales, the temporal change of cloud structures is mainly caused by cloud motion. An approach for forecasting was developed, based on the calculation of motion vector fields from satellite images (Lorenz et al., 2004). The algorithm consists of the following steps:

- As a measure of cloudiness, cloud index images according to the Heliosat method (Hammer et al., 2003), a semi-empirical method to derive solar irradiance from satellite data, are calculated from the satellite data.
- Motion vector fields are derived from consecutive cloud index images.
- The future cloud situation is determined by applying the calculated vector field to the actual image
- A smoothing filter is applied to eliminate randomly varying small-scale structures that are not predictable.
- Solar surface irradiance is derived from the predicted cloud index images using the Heliosat method.
- Accuracy information for the irradiance is provided.

This section gives a short overview on the used data, methods and results.

2.1 Satellite Data

Images in the visible range of the geostationary METEOSAT satellite are used as input data for the forecast.

The Meteosat satellites at prime meridian position (0° North / 0° East) view basically Europe, Africa, and the eastern part of Brazil. The satellites of the new generation provide images of the full Earth disc every 15 minutes with a spatial resolution of approximately 1 km x 1 km at sub-satellite point, where the proceeding satellites had a temporal resolution of 30 minutes and a spatial resolution of 2.5 km x 2.5 km.

The forecasting approach proposed and the results presented here, were developed on base of Meteosat 7 data. Currently, the method is adapted to MSG with special focus on the possibilities for improvement due to the enhanced spatial and temporal resolution.

2.2 Irradiance from satellite data

The surface irradiance and information on clouds are derived from the satellite measurements using an enhanced version of the Heliosat method. As a measure of cloudiness a dimensionless cloud index value *n* for each image pixel is derived. A basically linear relation ship is assumed to describe the influence of the cloud index on the atmospheric transmittance. The global irradiance is calculated by combining the information on the atmospheric transmittance with a clear sky model.

Typical deviations of hourly satellite-derived global irradiance from ground truth data are 20-25% of relative root mean square error (RMSE) for Meteosat 7. For the new satellite generation MSG and using further enhanced irradiance calculation schemes these errors are reduced with a factor of approx. 0.9. The quality of the satellite-derived irradiance provides a lower limit for the forecast accuracy.

2.2 Forecast of cloud development

The forecast algorithm for very short-term time scales operates on cloud index images and is therefore independent of the diurnal pattern of solar irradiance. This allows focusing on the development of cloud structures.

Motion vector fields are derived from consecutive cloud index images using the basic assumption that the change of cloud structures is dominated by cloud motion for short-term time scales. Several approaches to derive motion vector fields have been analysed (Beyer et al., 1994; Hammer et al. 1999 Lorenz et al., 2004). Using the algorithm proposed by Lorenz et al., the following model is applied to calculated motion vectors: Corresponding regions are identified within two consecutive images according to the assumption that pixel intensities remain constant during the motion. The criterion for an optimum displacement vector is the minimum mean square pixel difference for a rectangular region. For the application to MSG data modifications of this procedure are currently investigated.

The calculated motion vector field is applied to the current image to derive the forecast image, as illustrated in Fig.1.

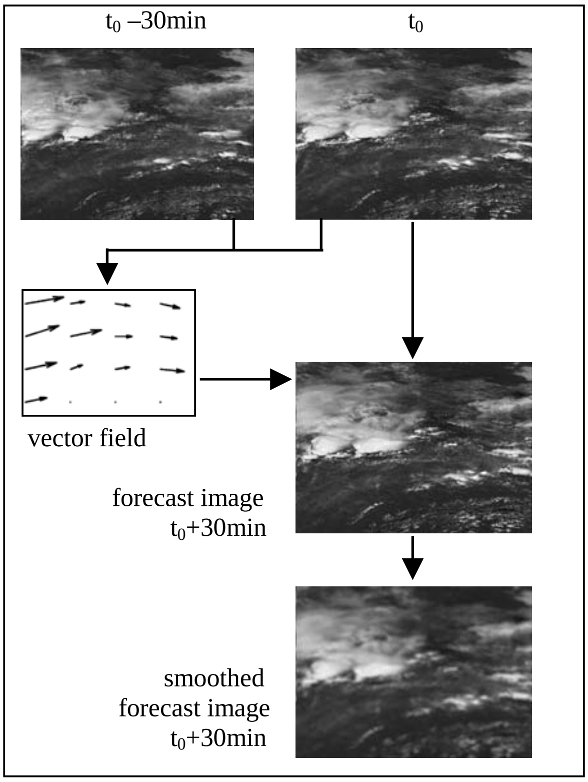


Fig. 1: Short-term forecasting scheme.

Finally, the influence of randomly varying small-scale structures is reduced by application of smoothing filters.

2.3 Forecast Accuracy

For an evaluation of the overall error, the forecast results were compared to half-hourly ground measured irradiance data from a regional measurement network for global irradiance (region of Saarbrücken, Germany, period 4/1995-3/1996).

Fig. 2 shows the RMSE of the global irradiance forecast. The forecast algorithm significantly reduces the errors compared to persistence. With increasing forecast horizon the influence of smoothing becomes more important compared to the application of motion vector fields. The Heliosat method considerably contributes to the overall deviation, especially for very short forecast horizons.

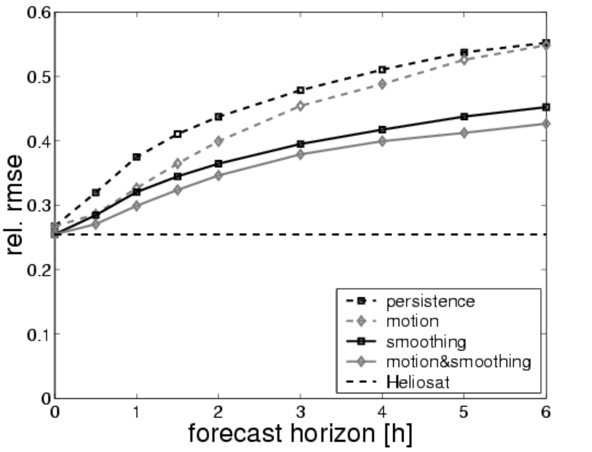


Fig. 2: Relative RMSE of global irradiance forecast depending on the forecast horizon, calculated for a one year period in Germany (eight stations in an area of 31 km x 45 km). For comparison, forecasts based on persistence, on application of a smoothing filter and on motion vectors only are displayed. As a lower limit the deviation due to the Heliosat method only is given.

An accurate specification of the forecast accuracy is an important issue for an effective application. Therefore, a detailed error analysis was performed to distinguish situations with different forecast quality. Situations with inhomogeneous clouds generally are more difficult to forecast and usually show larger errors than clear sky days. This is illustrated in Fig. 3, where two typical situations with different accuracies are shown.

In order to quantify the expected errors, different classes of forecast quality were defined and the expected accuracy for each class was determined. Here, the influence solar zenith angle on forecast accuracy is taken into account. Furthermore, different weather situations are characterized by the cloud index and the pixel variability within the cloud index images. These parameters influencing the forecast quality are extracted from the actual satellite images in order to be able to provide an accuracy forecast for the predicted irradiance values.

For large solar zenith angles and highly variable clouds the forecast errors exceed 40% for all forecast horizons. On the other hand, the forecast is very accurate in cases of high irradiance with low spatial variability and sun elevations higher than 20^o. The errors for half-hourly irradiance values range from 10% for a forecast horizon of 30 minutes to 25% for a forecast horizon of 6 hours.

Further improvements of the irradiance forecast are expected with the use of high-quality MSG data.

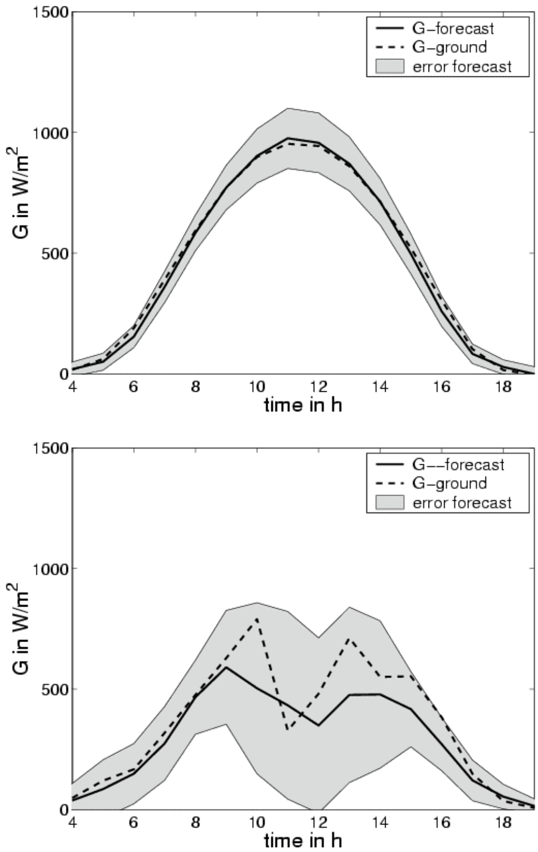


Fig. 3: Forecast error ranges depending on the irradiance situation. Ground measured (solid line) and forecasted (dashed) irradiance for a clear sky (top) and a broken cloudy (bottom) day. The grey area represents expected maximum error of the irradiance forecast.

3. IRRADIANCE FORECASTING BASED ON NUMERICAL WEATHER PREDICTIONS

Very short-term forecasting of global solar irradiance with a limited time horizon of approximately 6 h is not sufficient for an efficient planning and operation of solar energy systems. Especially for the grid integration of solar energy forecasts for up to 48 h or even beyond have to be provided. Numerical meteorological models may have the potential to satisfy the requirements in forecasting solar irradiance. A meteorological model is any model which allows calculating fields of meteorological variables, e.g., wind speed, radiation, in the atmosphere. Global numerical weather prediction models (NWP) have usually a coarse resolution and do not allow for a detailed mapping of small-scale features. Therefore, the use of regional mesoscale models and the combination of a NWP model with statistical post-processing tools to account for local effects needs to be evaluated and are presented here.

3.1 Numerical Modelling

The PSU/NCAR mesoscale model MM5 is a three-dimensional, regional-scale model that can be configured hydrostatically or non-hydrostatically (Grell et al., 1995). It uses a terrain-following coordinate, solves its finite-difference equations with a time-split scheme and has multiple nesting capabilities. Parameterization of atmospheric radiation provides longwave and shortwave schemes that interact with the atmosphere including cloud and precipitation fields as well as with the surface.

MM5 is driven by parameters available from a global NWP model. The resolution of these data is typically 0.5 to 1 degree in space and 3 to 6 hours in time. MM5 performs spatial and temporal scaling and the calculation of the solar irradiance. The accuracy of MM5 forecasts of solar irradiance and the dependency on different MM5 configurations as well as on different input data is still not known in detail. Only a few studies have investigated MM5 estimations of solar irradiance for single locations (Armstrong, 2000; Zamora et al., 2003). Extended studies on regional forecasts of solar irradiance are still pending.

Therefore, a case study of using MM5 for forecasting surface solar irradiance for lead times of up to 48 hours for regions as well as for single locations has been carried out. In a first step different MM5 configurations and their downward short-wave radiation results were compared to determine the best set-up. For this purpose MM5 has been initialized with reanalysis data from NCEP (National Center for Environmental Prediction) with a (1°x1°, 6 h) resolution. The configuration test and the first forecast runs with the best set-up are done by case studies. Three different cloud situations (clear sky , broken clouds, overcast) with a 48 h lead time were investigated. The results are computed as spatial averages for a region of 150x150 km with a horizontal grid size of 3x3 km, 23 vertical layers and a temporal resolution of 1 h. The comparison of seven configurations shows significant differences in the error of the irradiance. For the clear sky situation the deviation of the daily sum is between 1 % and -15 %. The broken cloud situation is linked with higher errors (6 % to - 64 %) as well as the overcast case (-8 % to 130 %). The best configuration is defined to be the one which leads in all three cases to acceptable errors (2 %; 7%; 26 %).

The best configuration was used in the forecast test case with data from different sources and with different resolutions as initialization. First results show a good agreement between measurements and forecasts for clear sky situations and the effect caused by different input sources is negligible. In case of broken clouds and overcast situations the deviations increase significantly and the applied input source has a strong influence on the accuracy of the forecast (Fig. 4).

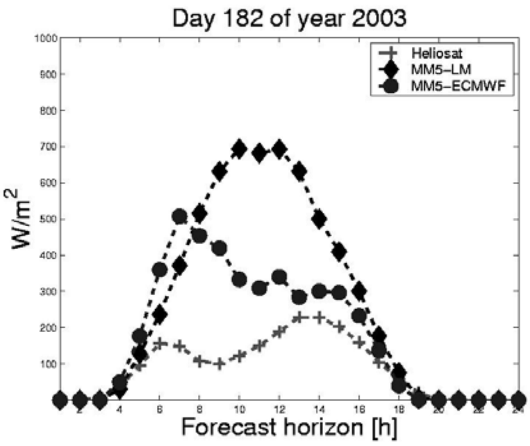


Fig. 4: Comparison of MM5 forecasts and satellite-derived Heliosat data for a day with broken clouds. One MM5 forecast with ECMWF and the other with DWD-LM initialization.

This result can be also determined by a additional investigation, which has been performed for a period of 40 days in summer 2003 for a 200 km x 200 km region in Germany. Again, ECMWF and DWD LM-6h data are used for initialization. The results are compared to ground measurements of eight ground stations, to satellite derived Heliosat data and to results from an operational MOS forecast (Fig. 5). The MM5 runs with ECMWF initialization delivers better forecasts than those with DWD initilization.

A second approach in using a mesoscale model for solar irradiance forecasting is to predict parameters describing cloudiness. After converting, this information can be used within the Heliosat method to derive solar irradiance. In a similar way and after a temporal and spatial scaling the cloud parameters predicted by macroscale models may be used. The global macroscale model run by ECMWF already directly forecasts solar irradiance. The weakness is the low spatial and temporal resolution which can be overcome by different spatial and temporal integration techniques (Fig. 5). This results in a enhanced solar irradiance forecast based on the ECMWF radiation prediction. This approach also makes the integration of forecasts of aerosol type and amount a promising option. Fig. 6 shows the principal procedure.

MOS forecasts show a superior behaviour compared to MM5 results and the enhanced ECMWF forecast is the best.

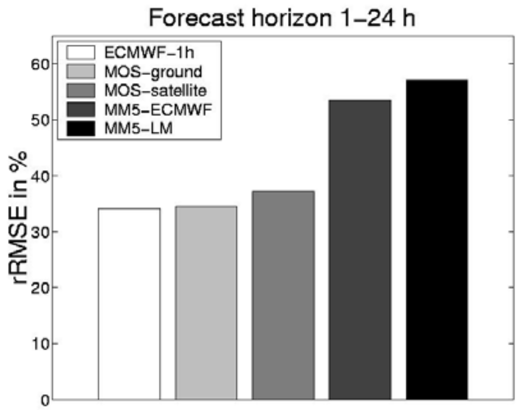


Fig. 5: Relative root mean square errors for regional 200 km x 200 km forecasts for one day, 40 days in summer 2003.

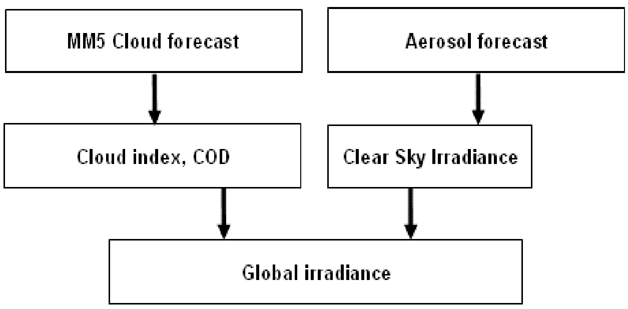
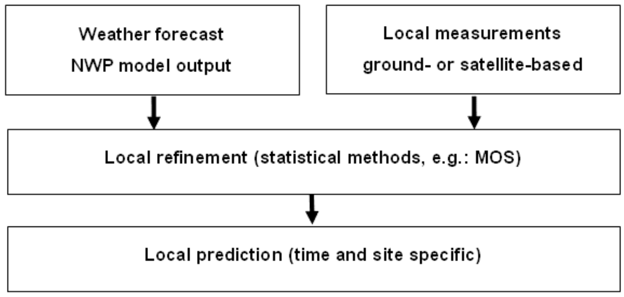


Fig. 6: Forecasting approach based on mesoscale numerical modelling.

3.2 Model Output Statistics

Model Output Statistics (MOS) is a post-processing technique used to objectively interpret numerical model output and produce site-specific forecasts. MOS relates observed weather elements to appropriate variables (predictors) via a statistical approach. These predictors may be NWP model forecast, prior observations, or geoclimatic data. MOS objectively interprets NWP model output based on a historical sample and therefore only predicts events which are forced by synoptic-scale systems. It may correct for certain systematic NWP model biases and quantify uncertainty in NWP model forecasts. It accounts for some local effects and incorporates climatic considerations. By principle, it cannot predict events forced by mesoscale features and correct for certain deficiencies in NWP model physics, analysis schemes, or parameterizations (Fig. 7). Also changes to NWP model components cannot be considered. Not every local effect may be accounted for as well as unusual climatic conditions.Fig. 7: Scheme of an operational



irradiance forecasting using Model Output Statistics (MOS).

Daily solar radiation forecasts for one to two days in advance can be produced using a multiple linear regression for maximum twelve predictors explaining each at least 0.1% of the total predictand variance (Jensenius, 1981). Approaches for clearness index, and irradiation directly, both for single station and regionalized were developed. Verification statistics showed a mean bias error (MBE) of 2 % and a RMSE of 25% for a 1-day-forecast.

Recently, a MOS based forecasting scheme for solar irradiance has been reported using ECMWF model output (Bofinger and Heilscher, 2004). Direct model output as well as statistically derived predictors were used. The most relevant predictors are: cloud cover index, dew point difference, 500 hPa relative humidity, dew point difference, cloud cover below 2000 m, probability of precipitation. Verification results for a one-year period (2002) and 32 German sites are given in Table 1. Bias errors are low for all forecasts, RMSE values show significant improvements over persistence with minor differences between ground-based and satellite-derived data.

Table 1: Verification results for ECMWF based hourly MOS forecast. Forecasts using ground and satellite-derived data are compared to persistence and to deviations introduced by the satellite technique HELIOSAT.

	RMSE [%]	MBE [%]
MOS, ground data	32.1	2.9
MOS, Meteosat data	34.9	2.3
Ground persistance	54.5	-0.2
Meteosat persistance	52.2	3.3
Heliosat	26.0	2.8

4. OUTLOOK

Only recently more work has been presented to improve solar irradiance forecasting. For one- or two-day forecasts the direct output from numerical macro- or mesoscale models has shown severe deviations between forecasted and real irradiance. This can be understood by the role of radiant fluxes in numerical models, which are important as a driver for atmospheric processes and to a much less extend for the production of precise surface solar irradiances. The indirect use of these models by using forecasts of variables which influence surface irradiance (clouds, humidity, etc.), seems to be a promising option. The coupling of these data with radiative transfer models then is a straightforward task. In the same sense, coupling of atmospheric and statistical models (as MOS is) still has strong potential for improvements.

5. ACKNOWLEDGMENTS

Forecast data have been kindly provided by the German Weather Service (DWD) and the European Centre for Medium Range Weather Forecasts (ECMWF). Ground measurement data are supplied by the German Weather Service.
Meteocontrol GmbH provided information on an operational MOS solar irradiance forecast. Validation results have been produced by Carsten Hoyer, DLR, in the framework of the ESA funded project ENVISOLAR.
Current research on solar irradiance forecasting reported in this paper is performed in the framework of the Virtual Institute of Energy Meteorology (vIEM) funded by the Helmholtz Gemeinschaft.

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