FORECAST OF ENSEMBLE POWER PRODUCTION BY GRID-CONNECTED PV SYSTEMS

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ABSTRACT: The contribution of power production by PV systems to the electricity supply is constantly increasing. An efficient use of the fluctuating solar power production will highly benefit from forecast information on the expected power production. This forecast information is necessary for the management of the electricity grids and for solar energy trading. This paper will present and evaluate an approach to forecast regional PV power production.

The forecast quality was investigated for single systems and for ensembles of distributed PV systems. Due to spatial averaging effects the forecast for an ensemble of distributed systems shows higher quality than the forecast for single systems. Forecast errors are reduced to an RMSE of 0.05 Wh/Wp for an ensemble of the size of Germany compared to a RMSE of 0.13 Wh/Wp for single PV systems.

Besides the forecast accuracy, also the specification of the forecast uncertainty is an important issue for an effective application. An approach to derive weather specific confidence intervals is presented that describe the maximum expected uncertainty of the forecast.

Keywords: PV system, grid-connected, solar radiation, forecasting

1   INTRODUCTION

Due to the strong increase of renewable energies the significance of the prediction of meteorological quantities such as wind velocity and solar irradiance is rising. Today, wind power prediction systems that improve the integration of wind energy into the electricity supply system are already available. Also the prediction of solar yields becomes more and more important for utilities with the increasing portion of solar energy sources. The Spanish feed-in law already includes incentives for correct prediction of solar yields for the next day.

Forecast information on the expected power output is necessary for the management of electricity grids and for solar energy trading.

We present a forecasting scheme to derive predictions of PV power output based on irradiance forecasts up to 3 days ahead provided by the European Center for Medium range Weather Forecasts (ECMWF). Additionally, the forecasted values are provided with confidence intervals. The specification of the forecast accuracy is an important issue for an effective application.

For the evaluation of the predicted PV system power output a database of about 4500 operating PV systems in Germany is available. The forecast quality is investigated not only for single PV systems but also for ensembles of PV systems. The ensemble production of all PV systems contributing to a control area is of interest for the utility companies.

This paper first presents the forecasting scheme and the applied models. This is followed by a short introduction to the quality measures used for the evaluation of the forecasts. In the fist part of the evaluation we give information on the forecast quality for irradiance and PV power output at single sites. Following, we present and evaluate an approach to derive confidence intervals for the forecasts. Finally, we provide an evaluation of the forecast for ensembles of PV systems.

2   FORECASTING SCHEME

2.1 Overview

The prediction of the PV power production is based on irradiance forecasts up to 3 days ahead provided by the global model of the ECMWF. Fig. 1 illustrates the different steps to derive a forecast of PV power production from ECMWF irradiance forecasts. For each step the used models and necessary additional information on the PV system is specified. In a first step, site-specific hourly forecasts are derived from the low-resolution ECWMF forecasts. In a second step, the forecast of the global horizontal irradiance has to be converted to the module plane with a tilted irradiance model. Finally, the power output forecast is obtained by applying a PV simulation model to the forecasted irradiances.

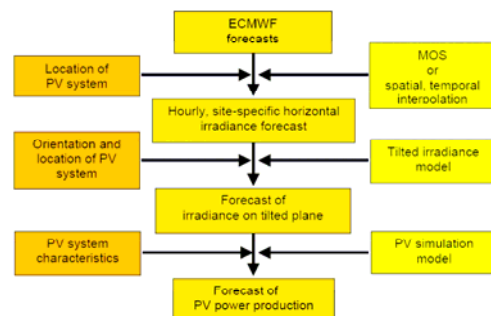The next sections shortly describe the applied models.

Figure 1: Overview on forecasting scheme.

2.2 Irradiance Forecasts

The global model run by the ECMWF provides forecasts of solar irradiance with a temporal resolution of 3h hours and a spatial resolution of 25km x 25km. But for the management of electricity grids forecasts of the expected solar power input are necessary on an hourly basis. In order to derive site-specific hourly forecasts, we analysed

different spatial and temporal interpolation techniques to refine the ECMWF global model irradiance forecasts. An optimum adjustment of the temporal resolution was achieved by combination with a clear sky model to consider the typical diurnal course of irradiance [1]. As a second option, a Model Output Statistics (MOS) based forecasting scheme for solar irradiance using ECMWF model output described by [2] is evaluated.

2.3 Power Forecast

The incoming irradiance is received on a tilted plane by most PV systems. Hence, the forecasted horizontal global irradiance has to be converted according to the orientation and declination of the modules for processing in the PV simulation model. Here, the anisotropic-all-sky model formulated by [3] is used.

In order to derive the power output forecast a robust simulation model for MPP performance is applied to the forecasted irradiance on the tilted plane, together with models of the efficiency characteristics of the inverter and the different system losses (see. [4]). The model returns the AC power fed to the grid as function of the incoming irradiance and the ambient temperature. Information on the ambient temperature is included as forecasted values, for the forecasting scheme using MOS. For the forecasts based on spatial and temporal interpolation to derive site-specific forecasts, measured temperature values from nearby meteorological stations are integrated.

3 QUALITY MEASURES

For the evaluation of forecast quality two error measures were calculated. The mean values of the errors:

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(x_{forecast,i} - x_{measured,i}),$$

and the root mean square error:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{forecast,i} - x_{measured,i})^2},$$

with $x=I$ for the evaluation of the prediction of the irradiance I, and $x=P=P_{ac}/P_{nom}$ for the power forecast. The normalisation of the ac power output P_{ac} to the nominal power P_{nom} of the PV system allows for a better comparison of different PV systems.

The error measures are calculated for hourly values. Only day values ($x_{measured,i} > 0$) are considered for the calculation of BIAS and RMSE.

Also relative values of the error measures (rRMSE, rBIAS) will be given in the following sections. Normalization is done with respect to mean ground measured irradiance or PV power production of the considered period.

For comparison forecasts based on the assumption of persistence are evaluated. The irradiance values of the current day are taken as forecast values for the next days at the same time. This very simple approach of forecasting is often used as a reference.

4 ACCURACY OF IRRADIANCE FORECASTS

A comparison of the two proposed approaches for forecasting was performed by [1] using ground measured

irradiance data of 18 stations of the German weather service (DWD) of the years 2003 and 2004. Both approaches show a similar forecast quality with a rRMSE of 35%-40% for the first forecast day, and perform much better than persistence with a rRMSE of about 60%. For the second and third forecast day errors are only slightly increasing to an rRMSE of 40% to 45% for the third forecast day.

For clear sky days the forecast quality is much better. Best results are achieved with the interpolation technique combined with a clear sky model, the rRMSE ranges from 15% for the first forecast day to 20% for the third forecast day. The respective errors for the MOS system are about 5%-10% higher.

5 ACCURACY OF POWER FORECAST FOR SINGLE PV SYSTEMS

For the evaluation of the forecast of the power output a database of about 4500 operating PV systems in Germany is available. The forecast for these systems was processed using the MOS irradiance forecasts. For a detailed analysis of the forecasts based on the interpolation technique an ensemble of 11 PV Systems distributed over an area of 200km x 120km in Southern Germany was evaluated for April and July 2006 by [5]. These two months with different meteorological conditions were chosen in order to investigate the influence of weather conditions on the forecast accuracy.

A validation of the forecast quality for predictions up to 24 hours for the year 2005 using the database of 4500 systems resulted in a RMSE von 0,13 Wh/Wp and a BIAS of 0,006 Wh/Wp. Fig. 2 shows the accuracy of the forecast over the year in comparison to persistence. The figure illustrates the considerable improvement compared to persistence.
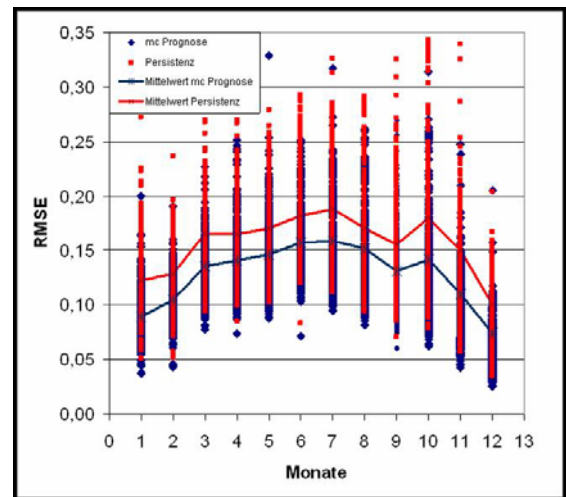

Figure 2: RMSE of hourly PV power production in Wh/Wp , red: forecast, blue: persistence. The mean value of all systems is denoted as solid line.

To illustrate the forecast accuracy, time series of predicted power output in comparison to measured power output are given for 7 days in April 2006 in Fig. 3, and for 7 days in July 2006 in Fig. 4 for a system of the ensemble in Southern Germany. In Fig. 4 also confidence

intervals are displayed that will be further discussed in the next section.

The figures shows that there is a good agreement between forecast and measurement for clear sky days with only minor underestimation of the actual power output. For cloudy days significant deviations between forecast and measurement may occur. For overcast situations a considerable overestimation of the power output can be observed (see Fig.3, 17th April). Furthermore, the strong variation of the power production for days with variable clouds is not correctly modelled by the forecast.
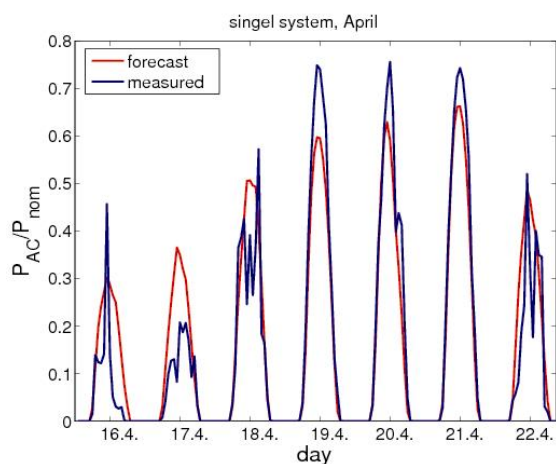

Figure 3: Predicted power output compared to measured power output for seven days in Aril 2006 for a PV system in Southern Germany.

A quantitative evaluation of the power forecast for the small ensemble of 11 PV systems resulted in a rRSME of 49% (absolute RMSE=0.12Wh/Wp) for April where cloudy situations were predominant. For July with mostly clear sky days for this region a lower rRMSE of 30% (absolute RMSE=0.10 Wh/Wp) is found.

This analysis was complemented with the evaluation of predictions of irradiance on the tilted plane at the PV system sites, and an analysis of global horizontal irradiance forecasts for meteorological stations located in the same region. The errors of the PV power forecast are very closely related to the errors of the tilted irradiance forecast, and the RMSE values are similar. This holds only if the PV system parameters used for the simulation have a good quality, which was the case for the evaluated systems.

The quality of the global horizontal irradiance forecast with a rRMSE of 44% for April and a rRMSE of 28% for July is slightly better than the quality of the tilted irradiance and PV power forecast. Forecast errors are amplified by conversion of the irradiance on the tilted plane. But, given correct parameters to characterize the PV systems, the accuracy of the global horizontal irradiance forecast is still the determining factor for the quality of the power forecast.

6 CONFIDENCE INTERVALS

The specification of the forecast accuracy is an important issue for an effective application of the forecasts. Therefore, confidence intervals are provided that indicate the range in which the actual value is expected to appear with a quantified probability (see illustration in Fig. 4).

To derive the limits of the confidence intervals, a model for the distribution of the scatter of the actual value around the forecast is needed. As the range of possible values is limited by zero and the power output at clear sky conditions, a natural choice for a respective distribution model is the beta distribution, already applied in the context of wind power forecasts [6]. This model is applied to the small ensemble of 11 Southern German PV systems.
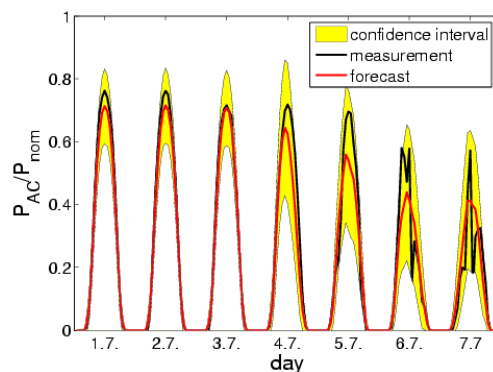

Figure 4: Predicted power output with confidence intervals compared to measured power output for seven days in July 2006 for a PV system in Southern Germany.

Basis for the determination of the confidence intervals is the knowledge of the situation-specific RMSE of the forecast. Together with the forecasted value itself it may define the beta distribution for the expected actual values.

These specific RMSE values are determined with dependence on sun elevation and cloud situation (homogeneous or scatter) using BIAS-corrected forecast values.

For this analysis only a limited number of measurements was available. Therefore, only three different classes of cloud situations are distinguished: clear sky, overcast, and broken clouds. The characterization of the classes was based on the mean clear sky index and the standard deviation of the clear sky index of the forecast field of all 11 PV systems. The clear sky index k* is a measure of cloudiness, defined as the ratio of global irradiance to clear sky irradiance.

Given the beta distribution, the limits of the confidence interval can be directly calculated. Here, we choose a confidence level of 90%. Fig. 5 shows an example for the derived confidence intervals for April and sun elevations between 40° and 50° for the three different classes of cloud situations. The figure illustrates that the confidence intervals provide a reasonable estimate for the expected maximum deviation of the measured from the predicted values. However, a considerable number of values also is found outside the confidence intervals. A quantitative evaluation revealed, that only about 80%-85% of the measured values are found within the confidence intervals for each class instead of the expected 90%.

Reasons for this insufficiency may be found in the fact, that the choice of only two parameters (mean value and spatial standard deviation the clear sky index k*) to derive the RMSE data is insufficient, especially taking into account that the systems analyzed show different

orientations and thus different responses to the cloud situation. Further analysis has to deal either with system specific RMSE values or the analysis of ensemble values and judge about the applicability of the distribution model on that bases.
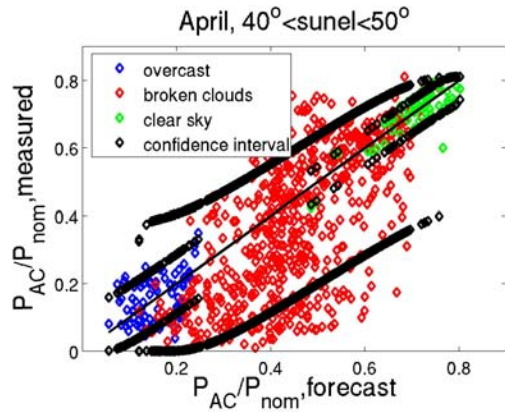

Figure 5: Measured power output over predicted power output with confidence intervals for 11 PV systems in Southern Germany. The predicted values are BIAS-corrected for each class separately.

Fig. 5 also illustrates that the different forecast quality for different meteorological situations is modeled well by the proposed approach. For clear sky situations the confidence intervals are chosen very narrow, the forecast is very reliable. On days with variable clouds large deviations are to be expected for forecasts with an hourly resolution for single PV sites.

7 QUALITY OF FORECAST FOR ENSEMBLES OF PV SYSTEMS

For the management of electricity grids and solar energy trading the ensemble production of all PV systems contributing to a control area is relevant.

7.1 Reduction of forecast errors for ensembles of PV systems

Due to spatial averaging effects the forecast for an ensemble of distributed systems shows higher accuracy than the forecast for single systems. Fig. 6 shows a time series of the power production of the small ensemble of 11 PV systems for seven days in July and the respective forecasts. Spatial averaging effects cause a smoother course of the curve of power production than for single systems (see Fig. 4) and the deviations between forecast and measurement are smaller.

For the ensemble of 11 PV systems forecast errors are reduced to a rRMSE of 39% (absolute RMSE=0.09Wh/Wp) for April and to a rRMSE of 22% (absolute RMSE=0.06) for July when considering the power production of the complete ensemble. This corresponds to an error reduction factor $r=RMSE_{ensemble}/RMSE_{single}$ of about 0.7.

For the large ensemble of about 4500 PV systems the evaluation of the ensemble power production forecast resulted in a RMSE of 0.052Wh/Wp, which corresponds to an error reduction factor of 0.4 for the complete year and the region of Germany.
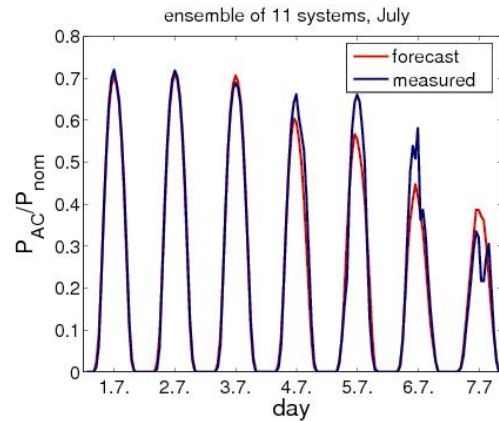

Figure 6: Predicted power output compared to measured power output for seven days in July 2006 for an ensemble of PV systems in Southern Germany.

7.2 Correlation of forecast errors

The reduction of errors when considering an ensemble of PV systems instead of a single system is determined by the correlation of forecast errors of the systems that are part of the ensemble.
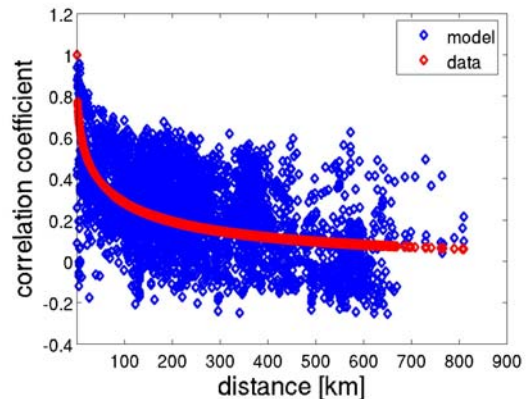

Figure 7: Correlation coefficient of forecast errors of two systems over the distance between the systems. The blue dots represent measured values; the red dots give the model curve.

The correlation coefficient of the forecast errors of two systems depends of the distance between the systems, as illustrated in Fig. 7. Here the correlation coefficient between two systems is displayed over the distance between the systems for the large German ensemble. The dependence of the correlation of the forecast errors on the distance of two systems can be modelled with an exponential function. The red line in Fig. 7 shows the model curve.

This model in combination with a statistical approach to derive the expected errors of mean values allows for the estimation of forecasts errors for arbitrary scenarios of ensembles of PV systems.

7.3 Evaluation of irradiance forecasts for distributed systems depending on the number of systems and the size of the region

A detailed analysis on the reduction of forecast errors, when considering ensembles of distributed systems, was performed by [5] using measured irradiance data of about

100 meteorological stations in Germany. As the accuracy of the PV power production forecast is mainly determined by the accuracy of the irradiance forecasts, the result of this investigation also gives information about the quality of PV power forecasts for ensembles of distributed systems.

[5] investigated the dependency of the forecast quality on the number of systems and the size of the region, where the systems are distributed. The distribution of the meteorological stations and the position and size of investigated regions is shown in Fig. 8. The evaluation was performed for the month April and July 2006. For April, where cloudy situations were predominant, a RMSE of 160 W/m^2 is found for single stations, when evaluating the complete ensemble. In July 2006 with mainly sunny days a considerable smaller RMSE of 110 W/ m^2 is obtained.
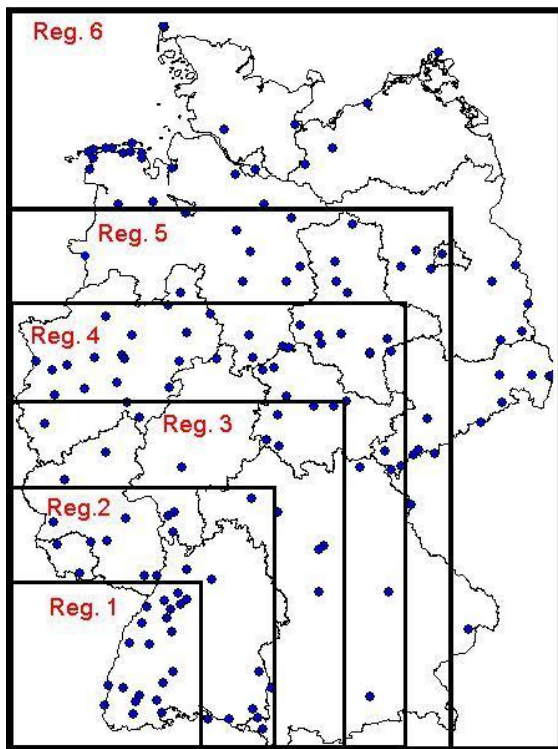

Figure 8: Distribution of the meteorological stations and position and size of the regions used for the evaluation.

As described in the previous sections, for mean irradiance values for an ensemble of stations the accuracy is increasing. Fig. 9 shows the rRMSE of the forecast of the mean irradiance of the ensemble over the number of considered stations for region 6 (Germany). The subsets of stations were chosen manually to cover the complete region with a mostly uniform distribution. Already for a small number of sites a large reduction of the forecast errors is achieved. With increasing number of sites and decreasing distance between the stations the correlation between the forecast errors is increasing (see Fig. 7). Consequently, the additional reduction of forecast errors when adding further sites to the ensemble is decreasing.

In Fig. 10 the reduction factor RMSE$_{ensemble}$/RMME$_{single}$ is displayed over the size of the region. Form each region 20 uniformly distributed stations were chosen to calculate the reduction factor. For small regions of about 200km x 200km a reduction factor of about 0.6- 0.7 is found, for a region of the size of Germany a reduction factor of about 0.4-0.5 is obtained. This in accordance with the results for the power forecast.
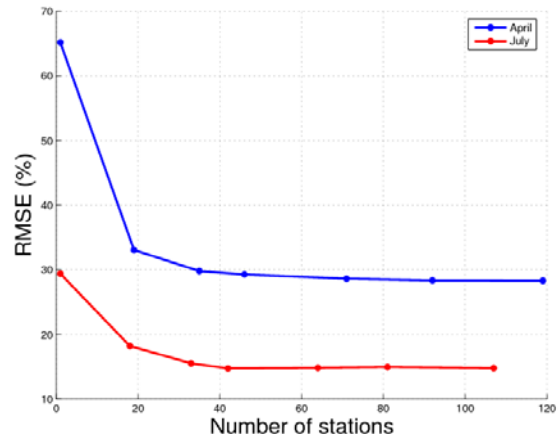

Figure 9: rRMSE of the forecast of the mean irradiance of an ensemble of stations in dependence on the number of stations.
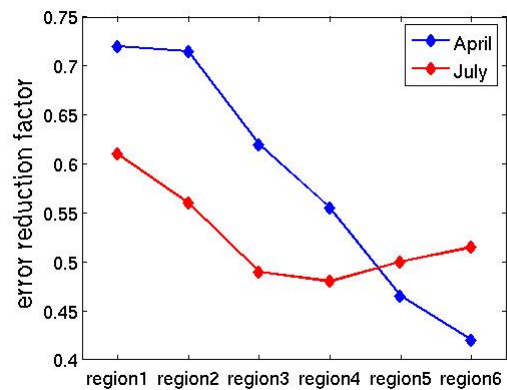

Figure 10: Error reduction factor RMSE$_{ensemble}$/RMAE$_{single}$ for regions with increasing size (see Fig. 8).

8 RESULTS AND CONCLUSIONS

An approach to forecast regional PV power production was presented based on refined ECMWF irradiance forecasts in combination with a PV simulation model.

The evaluation for hourly irradiance forecasts for single sites resulted in an overall rRMSE of about 35%-40%. This leads to a RMSE of about 0,13 Wh/Wp for the power forecast for single systems. The forecast quality depends on the meteorological situation: Situations with inhomogeneous clouds generally are difficult to forecast and show a lower accuracy than forecasts for clear sky days.

The specification of the forecast accuracy is an important issue for an effective application. An approach to derive weather specific confidence intervals was proposed and evaluated. The derived confidence intervals provide a reasonable estimate for the expected maximum deviation

of the measured from the predicted values for different meteorological situations.

Due to spatial averaging effects the forecast for an ensemble of distributed systems shows higher quality than the forecast for single systems. The increase of the forecast quality essentially depends on the size of the region, where the PV systems are distributed. For a region of the size of Germany the forecast errors are reduced by a factor of about 0.4-0.5. This corresponds to an absolute RMSE of 0.05 Wh/Wp.

The proposed approach to forecast power production of PV systems including confidence intervals can contribute to a successful integration of this fluctuating energy source to the electricity grid.

8 REFERENCES

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