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Continuous short-term irradiance forecasts using sky images

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Abstract

We present a system for forecasting occlusions of the sun and the expected Global Horizontal Irradiance (GHI) for solar power plants. Our system uses non-rigid registration for detecting cloud motion and a Kalman filter to establish continuous forecasts for up to 10 min. The optimal parameters of the system are determined through the use of the binary classification metrics Precision, Recall and F_2 Score while evaluating the forecasting of occlusions. The Kalman filter and the use of a dense motion field instead of a global cloud speed prove to be key elements of the forecasting pipeline: by incorporating information from previous forecasts into the current one, a Kalman filtering facilitates forecasting times below 3 min and the dense motion field enhances the accuracy of our forecasts. Our evaluation of the proposed approach on 15 days of real world data collected in Kitzingen, Bavaria, Germany, produced a mean RMSE for forecasting GHI of $(164 \pm 9)\ \mathrm{W\,m^{-2}}$.

Keywords: Solar forecasting; Sky imaging; Global Horizontal Irradiance (GHI); Intra-hour forecast

1. Introduction

An important factor for the wider adoption of photovoltaics (PV) as a renewable energy source on a larger scale, is stable power production. This is a challenging task since sun-occlusion effects by clouds can cause significant variability in the power output of solar power plants. Unaccounted changes in the future production of the power plant may either lead to an overproduction of power, or it may require the compensation of underproduction by additional power sources at short notice. Both of these events decrease the cost effectiveness of the power plant and should, therefore, be avoided. One way to improve the profitability and reliability of solar power plants is by forecasting the future power production, and therefore allowing for an earlier adjustment to the present conditions. We propose a new methodology for estimating upcoming sun occlusions for forecasts of up to 10 min (depending on the current cloud speeds) by analyzing sky-images acquired from the ground.

Our forecasts are quasi-continuous and describe the probability of the sun being occluded in a step size as small as 2 s. From such forecasts, one can calculate the periods of time in the future when the sun is going to be occluded. The main contributions of this work are:

- The generation of continuous forecasts for time intervals of up to 10 min, depending on the current cloud motion speed, instead of individual time-instance forecasting.
- The application of non-rigid registration to the task of estimating the cloud speed. Instead of a global cloud speed, we determine the cloud speed individually for different distances to the sun, thus the proposed method gains flexibility to account for deformations of the clouds.

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- The use of a Kalman filter (Kalman, 1960) to improve the accuracy of the forecast by incorporating knowledge from previous forecasts. The result is a continuous forecast also for forecasting times below 3 min.
- The quantitative evaluation of occlusion periods on real world data using Precision, Recall and F_2 Score as metrics, as well as the evaluation of our method using the Root Mean Square Error of predicted irradiance and the forecast skill. Our proposed method outperforms the persistence baseline even for short forecasting times.

The remainder of this paper is structured as follows. In Section 2 we present the current state of the art for forecasting PV power production. Section 3 contains a detailed description of our method and in Section 4 the conducted experiments and their evaluation are presented.

2. State of the art

The approach used for predicting the solar irradiance depends on the desired time scale of the forecast. For longer forecast times, in the range of 6 h to several days, numerical weather models can establish predictions for the expected irradiance for whole regions of interest (Lorenz et al., 2009). For predictions over a couple of hours, the cloud velocity can be extracted from satellite images. By extrapolating the trajectories of clouds in these images, the effects of occlusions can be predicted (Kidd et al., 2009). For an even higher temporal resolution, reaching down to several minutes, sky images recorded from the ground (Chow et al., 2011), or time-series models that rely on the knowledge of historical data (Reikard, 2009) can be employed. Our method only uses ground-based sky images. We will, therefore, concentrate on the comparison to similar methods in this brief overview of previous work. For more detailed information on the other types of methods, one may refer to the recent review by Inman et al. (2013).

Chow et al. (2011) were the first to establish intra-hour forecasts for solar irradiance using a ground-based camera. For recording the image data a commercially available Total Sky Imager from Yankee Environmental Systems was used. Cloud segmentation was done by employing a threshold on the ratio of the red/blue channels of the images and by also comparing the sky images to a clear-sky model. Actual predictions are done by calculating the cloud speed using the cross-correlation of cloud patches, and then moving the cloud mask according to the determined cloud speed. The whole approach was evaluated on a four day dataset. However, the method and the used equipment have some drawbacks. The resolution of the acquired images is low, and the default automatic white-balancing can lead to problems in cloud segmentation. Furthermore, images are recorded in the JPEG format, which induces losses in image quality during compression. The method for assessing the cloud speed is not robust against non-rigid deformations of the clouds, and the quantitative part of the evaluation is restricted to how well the forecasted cloud map corresponds to the actual one. No irradiance data is used in the quantitative part of the evaluation.

An improvement in the cloud motion registration was proposed by Marquez and Coimbra (2013), who use particle image velocimetry (PIV), a technique commonly used in the experimental study of fluid dynamics. The cloud segmentation was also further improved by using an adaptive thresholding method, and by partitioning the sky image into several regions with different thresholds. For evaluation, Marquez and Coimbra used the Root-Mean-Squared error (RMSE) between the forecasted Direct Normal Irradiance (DNI) and the measured one.

Two publications built up on this work: Chu et al. (2013) further improved the forecasts by training an artificial neural network (ANN), while Quesada-Ruiz et al. (2014) replace the PIV approach by a sector based motion detection method. The ANN required as input the expected cloudiness calculated by the method of Marquez and Coimbra and the last few measured irradiance values. The result of the ANN was a 5 or 10 min irradiance forecast. The latter work by Quesada-Ruiz et al. (2014) divided the sky into sectors, and determined the direction of cloud motion by analyzing the changes of cloudiness in these sectors. Using the RMSE between predicted and measured DNI as a measure, the evaluation of both works showed an improvement over the previous work by Marquez and Coimbra.

Besides using ground-based images, there also exist approaches that only rely on a network of irradiance sensors. Lonij et al. (2013) for instance, established intra-hour forecasts using a network of 80 rooftop PV systems spread over a large area. For large but isolated solar power plants the cloud motion vectors could also be calculated using reference cells, as was shown by Bosch and Kleissl (2013). Both of these approaches, however, require additional hardware that has to be installed in a large region around the power plant. In comparison, the Sky Imager only requires a single camera that is usually located at the center of the power plant.

Further work has also been done on the segmentation and classification of clouds. Kazantzidis and Tzoumanikas (2012) augmented the cloud segmentation based on the red/blue ratio by also incorporating the green channel. Furthermore, they used texture features and a k-Nearest-Neighbor classifier to classify the type of cloud seen in an image. However, the classification is done for the entire image, so that sky conditions where more than one type of cloud is present lead to an ambiguous result.

3. Forecasting pipeline

We will first give an overview of the overall system architecture. The key components of our approach are then presented in greater detail in the remainder of this section.