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Forecasting of global and direct solar irradiance using stochastic learning methods, ground experiments and the NWS database

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Abstract

We develop and validate a medium-term solar irradiance forecasting model by adopting predicted meteorological variables from the US National Weather Service's (NWS) forecasting database as inputs to an Artificial Neural Network (ANN) model. Since the inputs involved are the same as the ones available from a recently validated forecasting model, we include mean bias error (MBE), root mean square error (RMSE), and correlation coefficient (R^2) comparisons between the more established forecasting model and the proposed ones. An important component of our study is the development of a set of criteria for selecting relevant inputs. The input variables are selected using a version of the Gamma test combined with a genetic algorithm. The solar geotemporal variables are found to be critically important, while the most relevant meteorological variables include sky cover, probability of precipitation, and maximum and minimum temperatures. Using the relevant input sets identified by the Gamma test, the developed forecasting models improve RMSEs for GHI by 10–15% over the reference model. Prediction intervals based on regression of the squared residuals on the input variables are also derived.

Keywords: Solar irradiance forecasting; Gamma test; Model input selection; Solar meteorology

1. Introduction

Although the radiation that reaches the top of the layers of the atmosphere is well defined and can be easily calculated, the solar irradiance that reaches the ground level where solar collectors (thermal and photovoltaic) operate depends strongly on localized and complex atmospheric conditions. From the operational standpoint, the balancing of supply and demand peaks in the electrical grid requires detailed consideration of the availability of solar power. Forecasting the available insolation is therefore an enabling technology for the success of any policy to include solar power as an important contribution to both centralized and decentralized systems. Cloud cover, aerosol content, and the presence of atmospheric gases in the troposphere (water vapor, carbon dioxide) and in the stratosphere (ozone) can reduce the availability of direct insolation at the ground level to a small fraction of the solar irradiance that reaches the upper atmosphere. These effects are particularly strong on the Direct Normal Irradiance (DNI). Because cloud cover corresponds to the strongest effect on ground insolation, no statistical method that ignores micro-scale ($\leqslant 2$ km) or meso-gamma scale (2–20 km) weather systems can succeed in estimating real-time and/or forecasting solar power availability.

The problem is substantially more complicated for the characterization of DNI, which is the component of the total solar irradiation that is most useful for solar concentrators. Solar concentrators that can concentrate in excess

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of 300 times the solar flux are considered viable technology alternatives for solar utilization, both for direct photovoltaic and solar-thermal conversion systems. In the case of concentrated PV, the rationale for concentration is primarily due to economics: the high-efficiency multi-junction photovoltaic cells that can achieve in excess of 40% direct radiation-to-electricity conversion in laboratory environments cost slightly more than 100 times the common PV cell. Recent studies also point out that the Energy Pay Back Time (EPBT) for multi-junction cells may be substantially shorter (see e.g., Fthenakis and Alsema, 2006; Pacca et al., 2007) than previously estimated. For solar-thermal conversion, high concentration designs are needed to achieve higher thermodynamic cycle efficiencies. Utility-scale solar thermal power system also use primarily DNI for both solar-tower and solar-trough power plants. Because most commercially viable, utility-scale solar technologies use high concentration technologies, DNI characterization is of critical importance in designing, implementing and deploying such power plants.

The purpose of this work is to produce hourly medium-term forecasting models for both the Direct Normal Irradiance and the Global Horizontal Irradiance (GHI) based on meteorological predictions from the National Weather Service's National Digital Forecasting Database (NDFD). The NDFD produces same-day up and to 7-days ahead forecasts of meteorological variables, not including solar irradiance. We refer to these forecasting time horizons as medium-term to be consistent with Perez et al. (2007), whom have recently developed and validated a forecasting model for GHI based on the sky cover data supplied from the NDFD. When applied to the Sacramento and New York areas, their forecasting model obtained accuracies consistent with preliminary analysis using Multiple Output Statistics and meso-scales models elsewhere (e.g. Heinemann, 2004). More recently, their model has been evaluated in a number of locations with widely different climates (Perez et al., 2010) and thus further validating the generalization of the simple model. The present study extends theirs by considering the use of additional meteorological variables in order to enhance the forecasting capabilities of the models. Because this study considers the use of a larger number of variables, we present and employ an objective strategy which helps to select inputs that contain the most predictive information.

The Gamma test (GT) is an appropriate tool for identifying relevant inputs, as this test has been demonstrated to be able to provide information regarding the relationship between input and output data sets, even prior to model development (Durrant, 2001; Jones, 2004; Wilson et al., 2004; Moghaddamnia et al., 2009; Remesan et al., 2008). The GT is an algorithm designed to provide an estimation of the lowest possible mean squared error (MSE) attainable by a continuous and differentiable model for some output, y, based on the inputs, $\mathbf{x}$. The criteria for choosing the content in $\mathbf{x}$ can be based on keeping the dimension of $\mathbf{x}$ small (to remove insignificant inputs), meanwhile retaining a low estimate for the MSE. The GT is a relatively simple algorithm to apply and is used here as a basis for the selection of relevant inputs. The selection procedure also involves a genetic algorithm (GA) search in order to efficiently explore possibly significant input combinations. In Section 3 the GT and GA procedures are described, and in Section 4 the input selection algorithms are evaluated.

After applying the GT and GA to identify which subsets of inputs are potentially useful, Artificial Neural Networks (ANNs) are used to construct the forecasting models. ANNs are described and applied in Sections 5 and 6. In Section 7, prediction intervals are derived which take into account the forecasting uncertainty based on the predicted NDFD-based meteorological conditions.

2. Data

The University of California Merced solar observatory is equipped with several total and spectral solar instruments acquired from Eppley Labs. Three integrating instruments were used extensively in the present study: 1 PSP (Precision Spectral Pyranometer) for benchmarking the global irradiance, 1 NIP (Normal Irradiance Pyrheliometer) for benchmarking the direct irradiance, and 1 SDK (Shaded Disk Kit) that shades another PSP mounted on a solar tracker to measure the diffuse irradiance. From measurements of two components irradiance the third can be calculated, (e.g., global and diffuse data can be used to calculate the direct). We used all three measurements to constantly monitor the quality of the data. Expected accuracies of the irradiance measurements are estimated to be on the order of 5% for PSPs, and 3% for the NIPs. Data acquisition, logging and processing is automated with the aid of a Campbell Scientific's CR1000 data-logger. The data sampling rate is two samples per second. The data logger calculates and stores averaged values for each quantity every 30 s – hourly averages are calculated from the logged values.

The National Weather Service (NWS) manages the National Digital Forecast Database (NDFD) which provides gridded digital forecasts of weather parameters for the entire country at high resolutions of up to 2.5-km spatial and 1-h temporal (Glahn and Ruth, 2003; Perez et al., 2007). Local forecasts from NWS Weather Forecast Offices (WFOs) are generated by national model outputs, meso-scale model runs and human input. These local forecasts are then merged and assembled on a national grid (Glahn and Ruth, 2003; Perez et al., 2007). Weather forecasted values are publicly available and can be accessed electronically in Extensible Markup Language (XML) format through the NWS website: http://www.weather.gov/ndfd (Schattel and Bunge, 2008). The forecasted meteorological elements provided by the NWS include ambient temperature, dew point temperature, relative humidity, sky cover, wind speed and direction, probability of precipitation, significant wave height, weather type, and snow amount. Daily maximum and minimum ambient temperatures are also provided by the NDFD.