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Structured, physically inspired (gray box) models versus black box modeling for forecasting the output power of photovoltaic plants

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A B S T R A C T

Two advanced models for forecasting the output power of photovoltaic plants are discussed in details: a black-box Takagi-Sugeno fuzzy model and a physically inspired, semiparametric statistical model (Generalized Additive Model, GAM) based on smoothing splines. The structure of the two models, their strengths and weaknesses, are presented. The models performance is thoroughly compared with the performance of a simple linear model tested under the frame of the European Cooperation in Science and Technology (COST) Action “Weather Intelligence for Renewable Energies”, as a benchmark used also in the forecasting exercise reported in Sperati et al. *Energies* 8 (2015) 9594. The models are used to forecasting the output power at time horizons of 1–72 h ahead. The data used during the COST competition are used here as input. The present study extends beyond the traditional evaluation of overall model accuracy. Detailed influences of seasonal effects, sun elevation angle and solar irradiance level upon the models performance are assessed. While the accuracy of the simple linear model is not entirely bad, it differs in important details from the two advanced forecasting models. The results show that a moderate, carefully chosen increase in model structure complexity can improve the predictive performance. Suitable penalty on model complexity can help both to enforce parsimony and improve practical forecasting abilities, to a certain extent. The physically inspired GAM comes out as the best performing model.

1. Introduction

Unlike the power generated by the traditional power plants based on fossil or nuclear fuels, the output power of the wind and photovoltaic (PV) plants is highly variable to erratic. This variability is quantified in Ref. [1] based on measured time series of the year 2014 collected from the EU transmission system operators. The major time-dependent phenomena affecting PV plants operation are:

(1) Earth movements. They are deterministic by nature and therefore, during a clear sky operation, the output power of a PV plant can be calculated quite accurately over a variety of time scales.
(2) Cloud shading when clouds pass over the PV plant. This process is random by its nature. Since the response time of a PV plant is very short, the abrupt changes in the irradiance level due to passing clouds may induce abrupt changes in the output power. This strong variability is of concern for electric grid operators, because the unexpected and sharp changes in the output power of large PV plants may be followed by grid perturbations or damages [2].

The modern concept of intelligent grid management targets at adapting to the real time energy production, compensating both for the fluctuations of wind generators and PV plants, as well as for the fluctuations of energy demand. The operational algorithm of a smart grid includes procedures for forecasting the energy

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Nomenclature

NP	Nominal power [kWp]
GHI	Global solar irradiance [W/m^2]
DHI	Diffuse solar irradiance [W/m^2]
DNI	Direct-normal solar irradiance [W/m^2]
T	Air temperature at two meters high [°C]
TCELL	Solar cell temperature [°C]
NOCT	Nominal operating cell temperature [°C]
C	Cloud cover amount
β	Tilt angle of the PV modules [deg]
θ	Incidence angle on the PV module surface [deg]
ϕ	Geographical latitude [deg]
h	Sun elevation angle [deg]
δ	Sun declination angle [deg]
X*m*	Suffix *m* indicates that *X* is a measured quantity
Xf	Suffix *f* indicates that *X* is a forecasted quantity
XA	Suffix *A* indicates that X is a forecasted quantity by NWP adjusted to measured data
LT	Lead time [hours]

production of PV plants, playing an important role in the smooth, safe and efficient integration of these plants into the power distribution grid. Forecast horizons up to 72 h ahead are of particular interest for grids (partially) fed by PV plants [3]. The practical importance of this prediction horizon range is motivated both by technical reasons (e.g. constraints related to the start-up times of the conventional power plants used to compensate the power supply to the grid) and energy market perspectives (see Ref. [4] and the references therein). A framework for quantifying the integration costs of PV plants associated with subhourly variability and uncertainty as well as day-ahead forecasting errors is reported in Ref. [5].

Several research projects have been running all over the globe to test new ways for the accurate forecasting of the PV plants output power. One example of such a large scale project is the European Cooperation in Science and Technology (COST) Action ES1002 "Weather Intelligence for Renewable Energies" (WIRE) which was carried between 2011 and 2014 [6]. WIRE gathered members from 27 European countries and five non-COST institutions from USA, Canada, Australia and Japan. The Action was focused on two main lines of activity:

(1) To develop dedicated post-processing algorithms of wind and PV power coupled with weather forecasting models and measured data.
(2) To investigate the complex relationship between the highly intermittent weather-dependent wind and PV power prediction and the energy distribution toward the end users.

In the frame of the COST Action WIRE, a benchmarking exercise was organized with the scope of evaluating the performance of some state-of-the-art models of short-term forecasting the output power of wind farms and PV plants. The aim of the exercise was to bring together and evaluate the merits of forecasts based on different modeling approaches and input data. The benchmarking exercise and its results are comprehensively described in Ref. [7]. Forecasting the output power of PV plants is of concern in the context of our paper. The participants of the COST exercise received both meteorological and PV output power data covering periods of 1.5 and 2 years, respectively, from two Italian locations (Catania and Milano) to train and test their forecasting models. During the testing period, the measured power data were masked for the first 14 days of each month. The masked data were used by the organizers of the COST exercise to evaluate the models performance. An overview of the results was published in Ref. [7].

In this paper, we shortly present the forecasting model developed by our team in the frame of the COST Action "WIRE" benchmark exercise. It is a very simple physically motivated regression model which relates the output power to forecasted solar irradiance and estimated solar cells temperature on the base of the forecasted air temperature. Our previous positive experience with forecasting the PV output power was reported in Ref. [8]. The Numerical Weather Predicted (NWP) [9] data (solar irradiance and air temperature) provided in the training set by the COST exercise organizers have a large bias. Therefore, a first activity was to calibrate the NWP data against the ground measurements. The linear model constitutes a simple and straightforward way of calibration. Further details about the simple linear model are presented in Section 3.1.

Two new advanced forecasting models are presented in this paper. They were tailored to the needs of the typical PV forecasting. Thus, both models are able to forecast the PV plants output power at time horizons of 1–72 h ahead, as asked by grid operators in many countries. Also, they are based on NWP forecasts of radiometric and meteorological data, which are outcome of several popular regional circulation and weather prediction models. One of these new models is a black-box model developed in the frame of fuzzy sets theory [10]. Our previous studies showed that fuzzy sets theory has the ability to deal with large uncertainty in data: a study on the estimation of the global solar irradiance based on air temperature is reported in Ref. [11] while in Ref. [12] the fuzzy sets theory is used to forecast the daily global solar irradiation. This is particularly useful when scarce time series of forecasted meteorological data are available. Our other model is physically inspired, being based on the generalized additive model (GAM) theory. Its formulation is motivated by our previous GAM model applications for various solar energy forecasting problems reaching from fine time resolution modeling of binary sunshine indicator [13] to empirical modeling of temporarily aggregated solar irradiance [14], and also by a broader positive experience with penalized regression in a wide range of statistical modeling/forecasting problems in energy PV production [15], natural gas consumption [16] and public health modeling [17]. The particular GAM model used in this paper is purportedly formulated in a way that favors good forecasting performance close to the noon (where PV output is the largest) and accentuates less the early morning and late afternoon performance (when PV output is generally much smaller). We argue that this is the direction appropriate for PV power plants operation.

The structure of the paper is as follows. In Section 2, the data used during the WIRE benchmark exercise are presented. In order to illustrate how to build a particular model, in Section 3 the models and their development are described in detail. This part of the paper shows how to use in practice the NWP forecasted data (solar irradiance, air temperature and cloud amount) for prediction purposes effectively. A detailed analysis of the performance of all models is presented in Section 4. The simple linear model tested during the WIRE exercise is used as a benchmark for assessing the performance of the two new models. The dependence of models accuracy in respect to the lead time value is assessed. A sensitivity analysis to season, solar irradiance level and solar irradiance angle is performed subsequently. Discussion of the forecasting precision and how it compares among different model follows. Section 5 contains conclusions of our comparative study.