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Novel short term solar irradiance forecasting models

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ABSTRACT

The Angstrom-Prescott (A-P) type models are widely used for solar irradiance forecasting. These models use the sunshine duration and extraterrestrial irradiance values. The accuracies of the A-P models are highly region dependent coefficients. Therefore, these coefficients are determined empirically. In this study, five novel semi-empiric models for hourly solar radiation forecasting are developed. These models utilize historical data of the solar irradiance, the extraterrestrial irradiance and the clearness index while forecasting. To test the effectiveness of the proposed models, three different regions are deliberately selected, and solar data are measured and collected hourly. To show the effectiveness of the proposed models, the forecasting results are compared with the A-P type equation based models. The proposed approach is concluded to be superior compared with the previously developed A-P type equation based models.

1. Introduction

As the development of global economy continues, fossil fuels such as oil and coal are being depleted, environmental pollution and greenhouse effects are continuing to increase, and the energy crisis and environmental protection are becoming the focal points of sustainable development [1]. Due to the global warming and depletion of the conventional fuel sources, the interest on using clean and inexhaustible energy sources is growing. Among those sources, solar energy seems to be one of the promising options. Solar energy is a sustainable energy resource that can be considered an efficient alternative to fossil fuels [2] and critical to meet our energy needs [3]. Use of this untapped energy resource results in reducing carbon emissions and decreasing the economic and supply risks related to a reliance on fuels [4]. With a rapid reduction in cost in the last five years and having reached grid parity in various countries, solar photovoltaic (PV) electricity is poised to be one of the major future energy sources. However, the instantaneous power output of a PV system can vary substantially depending on local meteorological conditions and system's performance, which makes it an intermittent type of renewable energy with high variability [5]. Undoubtedly, accurate estimation of the solar radiation is an essential consideration for the optimal design of a solar system. Utilization of a precise model is of vital importance for areas with specific solar potential. Furthermore to reduce grid-integration costs, accurate and certain solar energy forecasts are required [6]. Therefore, developing accurate models for the estimation of solar radiation from available data is of great importance [4].

There are several methods used for solar radiation forecasting. Among them, intelligent methods are one of the most popular ones [7]. reported a new fuzzy model to forecast daily global solar irradiation at ground level. In their method, Fuzzy c-means clustering is used to establish the membership functions while the overall algorithm is developed in the frame of functional fuzzy systems. It is concluded that the model accuracy is adequate for routine practical purposes [8]. proposed a novel hybrid (Mycielski-Markov) model for hourly solar radiation forecasting. The model searches the longest repeated pattern in the past and according to the pattern, a prediction is made according to this pattern. To model the probabilistic relations of the data, a Markov chain model is adopted; by this way the historical search by the model is strengthened [9]. proposed a new hybrid technique to model the insolation time series based on combining Artificial Neural Network (ANN) and Auto-Regressive and Moving Average (ARMA) model. They proposed three different models and compared their performances [10]. used different kinds of ANN models (Delay based, Neuron based, Activation based, Multi-parameter based) to

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predict solar radiation. It was concluded that the most important factor for estimating hourly global solar radiation is the selection of the parameters envolved. In a different study [11], investigated the use of an adaptive wavelet-network architecture in finding a suitable forecasting model to predict daily total solar radiation. They considered total solar radiation as the most important parameter in the performance prediction of renewable energy systems and compared the results with different neural network structures. It was concluded that the training algorithms for wavelet-networks require smaller numbers of iterations when compared with other neural networks [12]. investigated the ability of FG (Fuzzy Genetic) approach in modeling solar radiation at seven cities in the Mediterranean region of Anatolia, Turkey. The latitude, longitude, altitude and month of the year were used as inputs to the FG model to estimate solar radiation one month ahead. The FG model was compared with ANNs and ANFIS (Adaptive Neuro-Fuzzy Inference System) models and it was found that the FG model can be successfully used for estimating solar radiation. These nonlinear forecasting methods are successful with nonlinear data, but such methods have computational complexity. Furthermore, ANNs are quite simple to implement. However depending on the structure of NN it is difficult to understand if the obtained output from the structure is the most accurate one.

Regression models are another important forecasting technique on solar radiation forecasting in the literature [13]. used both Auto-Regressive (AR) and AR with exogenous input (ARX) models and achieved an RMSE improvement of approximately 35%. AR models can determine current output, but their disadvantage is that they do not consider the past disturbances [14]. used multiplicative ARMA models to generate an hourly series of global irradiation. ARMA models are very flexible because they can represent several different types of time series by using different orders (the number of immediately preceding values in the time series). This method can predict when there is an underlying linear auto-correlation structure in the time series. For non-stationary time series one of the most popular statistical forecasting tools is a class of ARIMA models [15,16] [17]. showed that ARIMA works primarily because differencing at a 24-h horizon captures the sharp transitions in irradiance associated with the diurnal cycle more accurately than other methods. The use of ARMA and ARIMA provide a basis for many problems outside the realm of solar irradiance forecasting [16,18] [19]. proposed a novel approach based on similarity. In this approach, to predict next hour's solar irradiance data, a day similar to the prediction day is sought in the historical database. The similarity is determined based on the Euclidean distance metric and the predictions are made according to a day with similar pattern. The experimental results showed that the similarity approach provide good prediction performance [20]. proposed the use of linear prediction filters for hourly solar radiation forecasting. In this study the solar radiation values recorded in one dimension time series is converted to 2 dimensional matrix data whereas, first dimension is correspond to hours and second dimension is correspond to days. Afterwards, using this matrix 2 dimensional image views are obtained. By this way image processing techniques are able to be used. To improve the forecasting accuracy of this method [21], developed the multi-dimensional linear prediction filter approach. This approach provides the use of different data such as temperature and extraterrestrial radiation for estimating the solar irradiance values. In this method, each type of data is converted into a 2-D image. This approach links the images to each other using multi-dimensional linear prediction filters. To find the optimal coefficients for the filters, all of the pixels in each linked pattern are scanned. This approach provides improved accuracy for solar irradiance prediction (at rates ranging from 3% to 40%) in comparison with that by using linear prediction filters.

Empiric models are another popular solar radiation forecasting techniques. The Angstrom-Prescott equation is one of the widely used empirical methods [22]. proposed a linear relationship between the ratio of the average daily global radiation to the corresponding value on a completely clear day and the ratio of the average daily sunshine duration to the maximum possible sunshine duration. To address the difficulty in obtaining clear sky radiation data [23], suggested to use the extraterrestrial radiation instead; this modification led to the formation of the A–P equation:

$$R_s = \left(a + b\frac{n}{N}\right) R_a \tag{1}$$

where R_s and R_a are the global and extraterrestrial solar radiation values ($MJm^{-2}d^{-1}$), respectively; a and b are the A–P coefficients, the sum of which is the clear sky transmissivity; n and N are the actual and the theoretical sunshine duration in hours (h), respectively [24]. Other popular empirical models are the clear-sky ones. Different clear sky models are used for forecasting solar radiation. The clear sky solar radiation models are traditionally used in the design and the simulation of solar concentration systems. Additionally, they are of interest for filling in gaps in historical data [25]. The empirical models have the advantage of simplicity; however, they usually lack generality. In contrast, the radiative transfer models offer more generality and accuracy; however, these models are more complex and require more input data, which are not always available [26] [27]. employed semi-empirical corrections related to ground measurements, which led to under-prediction of solar irradiance at a high altitude aerostat [28]. proposed a semi-empirical direct solar model, which takes the effect of altitude into account, but the authors neglected the influence of altitude on the diffuse and reflected irradiance.

The persistence models propose that global irradiance at time $t+1$ is best predicted by its value at time t. The persistence forecast, which is also known as the naive predictor, can be used to benchmark other methods. The persistence forecast accuracy decreases strongly with forecast duration as cloudiness changes from the current state. Generally, persistence is an inaccurate method for more than 1 h ahead and should be used only as a baseline forecast for comparison to more advanced techniques [29]. In another study [30], the single-site performance of the forecast models was evaluated by comparing the models to persistence.

Alternatively, this study proposes some semi-empirical models for hourly solar irradiance forecasting. The proposed models use historical solar irradiance data, calculated values of extraterrestrial irradiance and clearness index data. The models were first evaluated using solar irradiance data from Afyonkarahisar collected from the solar observation station at Afyon Kocatepe University over a time period of 1 year (March 1, 2012–February 28, 2013). Then, these models were tested with solar irradiance data from different regions in Turkey and taken from the Turkish State Meteorological Service (DMI). Two different types (linear and quadratic) of A-P equations were applied to the same data, and the results were compared with the proposed models.

The organization of the paper is as follows: the data used for this study and the methodologies are described in Section 2. The experimental results are illustrated in Section 3. Finally, the conclusions are given in Section 4.

2. Materials and methods

In this study, solar irradiance data from different regions in Turkey were used. The cities used in this study are Afyonkarahisar, Ankara and Çanakkale; each city has different insolation characteristics, as shown in Fig. 1. Solar irradiance data for Afyonkarahisar