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Time series analysis of Bahrain's first hybrid renewable energy system

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A B S T R A C T

The performance of multisource renewable energy system depends strongly on the meteorological parameters pertinent to the energy generating systems. Therefore, a method of modelling and forecasting meteorological and system parameters is necessary for efficient operation of the renewable energy power management system. Bahrain's first hybrid renewable energy system utilizes two renewable energy sources, namely solar irradiance through a 4.0 kW_p PV (photovoltaic) panel and wind through a 1.7 kW_p wind turbine. The focus of the present work is to investigate the proficiency of the Box–Jenkins based modelling approach in analysing and forecasting the daily averages of wind speed, solar irradiance, ambient air temperature, and the PV module temperature. Different non-seasonal ARIMA (Autoregressive Integrated Moving Average) models have been constructed. ARIMA(1,0,0), ARIMA(1,0,0), ARIMA(0,1,2), and ARIMA(0,1,1) have been found adequate in capturing the auto-correlative structure of the daily averages of wind speed, solar irradiance, ambient air temperature, and PV module temperature, respectively. In addition, a functional relationship that correlates the diurnal PV module temperature to the ambient air temperature and solar irradiance have been developed. Residual and forecasting analyses have been used to ensure the adequacy of the identified models.

1. Introduction

The prevalent use of renewable energy system is limited by the unpredicted nature of its driving forces [1]. Therefore, different attempts have appeared in literature to forecast meteorological parameters that are pertinent to renewable energy systems. Suggested approaches are either deterministic, stochastic, or a combination of both and they are aimed to provide short-term forecasting (hours), medium-term forecasting (daily) or long-term forecasting (yearly). Wind speed, solar irradiance, ambient temperature, and PV (photovoltaic) module temperature have been identified as important parameters in determining the overall performance of any hybrid renewable energy system that consists of PV panels and wind turbines. Kamal and Jafri investigated several ARMA (Autoregressive Moving Average) models to forecast wind speed in Quetta, Pakistan [2]. A good agreement between the forecasts and actual wind speeds has been shown within the 95% prediction intervals. In addition, several non-Gaussian distributions have also been suggested to model wind speed [2]. Nasir et al. investigated the suitability of Weibull and Rayleigh density functions to fit wind speed data in Quetta, Pakistan as well [3]. They found that Weibull density function outperforms the Rayleigh density in fitting actual data. Carta et al. reviewed in details a wide collection of probability density functions which have been proposed in literature for wind energy analysis [4]. Once the parameters of an appropriate density function were identified, Monte Carlo simulation was used to generate forecasted values. A clear shortcoming of the probability density function modelling approach is its ignorance to the autocorrelation structure in the data. Different variations of time series modelling techniques have been used to assess energy-based systems. Javid and Qayyum used STSMs (Structural Time Series Models) to model the electricity demand function in Pakistan [5]. The structural form of the model allows the stochastic nature of the underlying energy demand trend as well as deterministic components, represented by the electricity consumption; to be model simultaneously with the real economy activity. Hu et al. utilized the concept of hybrid prediction to forecast wind speed in north-western China [6]. The hybrid model exploited the advantages of the EWT (Empirical Wavelet Transform), CSA (Coupled Simulated Annealing), and LSSVM (Least Square Support Vector Machine). CSA reduced the number of cost-function evaluations required by other search methods (e.g., neural

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network or simulated annealing) and was less sensitive to the parameter initialization required by the search methods. Poggi et al. used AR (autoregressive) model of order 2, AR(2), to simulate wind speed for 3 h in Corsica, France [7]. On the other hand, engineers and scientists often require accurate knowledge of the solar irradiance data for better utilization of the available resources. The latter is of importance for efficient planning, scheduling, and decision making processes in solar-related systems. Daily radiation has been also identified as an important parameter for better resources utilization of the renewable energy based systems [8,9]. Besharat et al. provided general classification of the solar irradiance models available in the literature [8]. They classified previously reported models into four main categories: sunshine-based, cloud-based, temperature-based, and other meteorological parameter based models. The widely used Angstrom–Prescott and Bahel models belong to the sunshine-based category. The model preference depends on the ease and availability of input measurements; for example, temperature is easier and more reliable to measure than the sunshine factor (S/S_o), where S is the monthly average daily bright sunshine-duration (usually measured in hours) and S_o is the maximum possible monthly average daily sunshine-duration. The aforementioned models are of deterministic nature and do not address the time autocorrelation. Bulut and Buyukalaca proposed a simple sinusoidal function with one independent variable, namely the day within the year, to forecast daily solar irradiance data [9]. Due to the harmonic nature of the solar radiation through the year, the inclusion of the day of the year as an independent variable has clearly improved the prediction of the deterministic variations in the data. However, the stochastic nature of the solar radiation time series has not been addressed. Sulaiman et al. fitted solar irradiance data from four different areas in Malaysia to three different time series models, namely, ARMA(1,0), ARMA(2,0) and ARMA(1,1) [10]. After extracting the deterministic harmonic components using Fourier Analysis, ARMA(2,0) was found best in describing the four studied locations. Zaharim et al. fitted ARMA(1,0) to solar irradiance data collected from Bangi, Malaysia using non-seasonal Box–Jenkins models [11]. While Zaharim et al. used only Ljung–-Box statistic to assess the randomness of the residuals, Sulaiman et al. used Ljung–Box statistics as long with skewness and the kurtosis coefficients of the residuals distribution to differentiate between the three fitted models. The latter explained the large variance of the residual distribution by the cloudy climate of Malaysia. However, neither Zaharim et al. or Sulaiman et al. have validated the prediction capability of the fitted models. Wu and Chan compared the proficiency of ARMA(1,1) and TDNN (Time Delay Neural Network) in forecasting hourly solar irradiance data after de-trending the solar irradiance time series to remove non-stationarity [12]. They also proposed a hybrid model that combines the strengths of both models under the assumption that the time series involves linear and nonlinear components. They fitted ARMA model to the time series and TDNN to the residuals. Forecasting from the hybrid model outperformed the ARMA or TDNN alone. Wang et al. proposed an optimized hybrid model that combined different machine learning algorithms such as CS (Cuckoo Search), OP-ELM (Optimally Pruned Extreme Learning Machine), FFNN (Feed Forward Neural Network), and MRSR (Multi-response Sparse Regression) to forecast hourly solar radiation data from six sites of the United States [13]. RMSE (Root Mean Square Error) and MRE (Mean Relative Error) were used to assess the proficiency of the developed models. ARIMA (Autoregressive Integrated Moving Average), BPNN (Back Propagation Neural Network), and OP-ELM were compared with the proposed CS-OP-ELM. Although CS-OP-ELM showed an overall better performance in forecasting clear and real sky global horizontal radiations, the complexity associated with the proposed hybrid model was weight by the relative prediction improvement. Dong et al. combined SOM (Self Organizing Map), SVR (Support Vector Regression) and PSO (Particle Swarm Optimization) to forecast hourly solar irradiance time series in Colorado, USA and Singapore [14]. While SOM was used to identify clusters in the input space with different characteristics, SVR and PSO were used to identify the data correlations and determine the parameters in the SVR model, respectively. The proposed hybrid model was also compared with ARIMA, LES (Linear Exponential Smoothing), SES (Simple Exponential Smoothing), and RW (Random Walk) models. While the hybrid model showed a marginal improvement, the normalized root mean square errors of the different models were comparable, therefore, favouring less complex models. The third meteorological parameter under study is the ambient air temperature. Similar to wind speed and solar irradiance, time series forecasting of the ambient temperature is essential for efficient energy management system. In addition, ambient temperature is pertinent to the performance of naturally-driven energy systems, such as the photovoltaic panel. Zhang et al. proposed an analytical model that related the air temperature in Singapore to the solar irradiance, clouds, ground heat radiation and heat convection [15]. Their model was derived using heat balance on a control volume of the atmosphere. Despite its physical causality, generally analytical models necessitate the availability of a large number of physical properties, e.g., air density, specific heat of dry air, etc., which are often difficult to obtain for different areas. Their model was incorporated into the energy management system scheme of a HVAC (Heating, Ventilation, and Air Conditioning) system. Chevalier et al. compared the prediction capabilities of two nonlinear empirical models, specifically, SVM (Support Vector Machine) and ANN (Artificial Neural Network) for short term forecasting of air temperature in Georgia, USA [16]. For 12 prediction horizons, SVM slightly outperformed ANN. This was attributed to the better convergence properties of SVM compared to ANN. In fact, limited papers have investigated the mid-term forecasting of air temperature using ARIMA time series analysis models. The fourth important parameter that determines the performance of a PV-containing hybrid renewable energy system is the PV module temperature. PV module temperature correlations found in literature can be classified as either steady state or transient models. In the steady state approach, parameter affecting the PV module temperature are assumed to be constant, whereas in the transient approach, these parameters change with time [17]. Steady state correlations can be further classified broadly into explicit and implicit forms. The explicit and implicit forms are functions of the pertinent weather variables, for example ambient temperature, local wind speed, and the solar irradiance flux [18]. Most of these steady state and dynamic correlations require the knowledge of the material and system properties of the renewable energy system's components which are difficult to obtain. Ceylan et al. used ANN to predict photovoltaic module's temperature for the Aegean region in Turkey [19]. In addition, sophisticated models based on Neuro-fuzzy and Kalman filter theories have been used for the dynamic forecasting of the meteorological parameters [20]. In general, the aforementioned empirical linear and nonlinear model-structures do not reflect the serial correlation among observations. In addition, it is well known that neural networks-based models are good interpolator, however, they commonly don't produce acceptable results when used for forecasting outside the fitting region. Alternatively, a simple and fast-to-build model was proposed in this study, which combined time series analysis and linear regression for the prediction of PV module temperature. ARIMA based time series models has been widely used in a variety of applications, for example management, finance, risk management, industrial process control [21], economics [22], demography, and climatology [23]. A fundamental assumption and key reason of the successful