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Stochastic analysis and simulation of hydrometeorological processes associated with wind and solar energy

Georgios Tsekouras*, Demetris Koutsoyiannis

Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 5, GR-157 80 Zographou, Greece

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ABSTRACT

The current model for energy production, based on the intense use of fossil fuels, is both unsustainable and environmentally harmful and consequently, a shift is needed in the direction of integrating the renewable energy sources into the energy balance. However, these energy sources are unpredictable and uncontrollable as they strongly depend on time varying and uncertain hydrometeorological variables such as wind speed, sunshine duration and solar radiation. To study the design and management of renewable energy systems we investigate both the properties of marginal distributions and the dependence properties of these natural processes, including possible long-term persistence by estimating and analyzing the Hurst coefficient. To this aim we use time series of wind speed and sunshine duration retrieved from European databases of daily records. We also study a stochastic simulation framework for both wind and solar systems using the software system Castalia, which performs multivariate and multi-time-scale stochastic simulation, in order to conduct simultaneous generation of synthetic time series of wind speed and sunshine duration, on yearly, monthly and daily scale.

1. Introduction

The drawbacks of conventional energy sources including their negative environmental impacts emphasize the need to integrate renewable energy sources, like wind and solar, into the energy balance. However these energy sources, unlike fossil fuels on which the past model was based on, are unpredictable, at both short and long run, and uncontrollable as they are associated with relevant hydrometeorological processes which are characterized by high variability and uncertainty [1]. As a result, the estimation of renewable energy sources requires analyzing hydrometeorological data, especially wind speed, sunshine duration and solar radiation time series.

Such hydrometeorological time series are typically modelled as stationary stochastic processes. In this case their probability distribution does not change in time. It is thus necessary, in order to characterize uncertainty, to assume a theoretical distribution function that fits properly the data. Normal distribution is suitable for most hydrometeorological processes at an annual or higher time scale due to the Central Limit Theorem. However, variables of lower time scales, such as monthly or daily, are characterized by skewness and thus, non-normal distributions are more appropriate for their representation. In particular, the sunshine duration is represented as a random variable bounded from both below and above, and thus a theoretical distribution with these properties should be chosen for its representation.

Various studies have been performed in order to examine theoretical distribution functions fitting properly wind speed and relative sunshine duration data. The Weibull and Gamma distributions have been found to be appropriate to represent wind speed data while the Beta distribution has been assumed to be suitable for the relative sunshine duration. Carta et al. [2] and Zhou et al. [3] proposed that both the Weibull and the Gamma distribution are suitable for hourly wind speed representation in the Canary Islands and in North Dakota respectively. Garcia et al. [4] and Yilmaz and Çelik [5] suggested that the Weibull distribution fits satisfactorily hourly wind speed data in Spain and Turkey. Darbandi et al. [6] noted that the Gamma distribution fits well the maximum annual wind speed data in Iran. Concerning the relative sunshine duration, Sulaiman et al. [7] and Bashahu and Nsabimana [8] examined the fit of the Beta distribution to daily data in Malaysia and Africa and concluded that it fitted satisfactorily the data in several cases. Chia and Hutchinson [9] examined the possibility of fitting the Beta distribution to daily relative cloud duration time series in Australia.

* Corresponding author.
E-mail addresses: georgtsek@yahoo.gr, georgtsek@hotmail.com (G. Tsekouras).

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In addition to the marginal distributional properties, the fact that climate is not static but exhibits fluctuations at all time scales should also be taken into consideration for the effective exploitation of renewable energy sources. In a stochastic framework, these fluctuations are quantified through the dependence of the processes in time [10]. While in several studies these processes have been regarded as independent identically distributed random variables, particularly at coarse time scales such as monthly or annual, other studies have verified the presence of dependence, sometimes long-range dependence, which has been also termed as long-term persistence (LTP), self-similar behaviour, or the Hurst–Kolmogorov dynamics. This long-range dependence expresses the tendency of similar physical events to cluster in time and its quantification is expressed through the Hurst coefficient, the mathematics of which is discussed later. The Hurst–Kolmogorov dynamics has been identified by several researchers in various environmental variables [11]. The British engineer Hurst [12] was the first to notice this behaviour while studying Nile's runoff and, earlier, the Russian mathematician Kolmogorov [13] had proposed a mathematical model consistent with this behaviour when studying turbulence. Later, this behaviour was also observed in other variables such as river runoff [14–20], temperature [21–25,17,26,27], climatic indices such as North Atlantic oscillation [28] and decadal Pacific oscillation [29] and atmospheric pressure fields [30].

So far, the concept of LTP has been incorporated in the modelling of runoff time series applied to reservoir sizing design studies, where it has been found that neglect of LTP usually leads to undersizing of the reservoir storage [31–34]. However, the Hurst–Kolmogorov behaviour has been found to be omnipresent in the most natural processes [11]. Consequently, it will strongly affect the design variables of any engineering project related to the exploitation of natural phenomena, like a large scale hybrid renewable energy system comprising wind and solar energy [35], as it expresses a general natural variability, manifested by the aforementioned fluctuations in multiple time scales [36,10]. Such large scale renewable energy projects aim not only at maximizing the profit but also the reliability in satisfying energy demand or energy target via storage of the excess energy in each time step of the project's operation, usually by means of pumped storage hydropower facilities. Therefore, neglect of this clustering of natural events at the design phase may lead to undersizing of the facilities for energy storage or overestimation of the reliability of produced energy.

A prerequisite for the investigation of Hurst–Kolmogorov dynamics is the analysis of time series having long time period records so that their fluctuations on multiple time scales can be detected. For this reason a sufficient time length (which is generally regarded 100 years or more and no less than 70–80 years) is required. However, hydrometeorological data records, relevant to wind and sun, started in the beginning of the previous century or later and as a consequence time series of such a length are not often available.

Once the marginal distribution and the dependence structure of the wind speed and sunshine duration processes are identified, another relevant issue is to construct a simulation model that can simulate such processes for arbitrarily long times, respecting the identified stochastic properties of each process, as well as the cross-correlation between the two processes. This issue is not trivial as typical stochastic generators may not be able to generate processes with non-normal distributions and with autocorrelations departing from a Markov process.

This study aims to perform a comprehensive analysis of existing data with sufficient length of observation, concerning wind speed and sunshine duration, retrieved from measuring stations all over Europe, in order to investigate the properties of their marginal distributions and mainly to detect the possible presence of LTP by estimating and analyzing the Hurst coefficient values of both processes.

At the same time, it also aims to construct a general stochastic simulation scheme, able to reproduce the statistical characteristics of the natural series including their long term variations. By this, the unpredictable fluctuations characterizing the natural resources (wind and solar radiation) can be taken into account effectively in the design and management of renewable energy systems that comprise both wind and solar systems, and possibly hydropower systems with pumped storage, which provide means for energy storage. The framework is particularly useful to study the reliability in fulfilling the energy demand or the energy production target. This is attempted by using the multivariate stochastic simulation system, Castalia, for the simultaneous generation of long synthetic time series, on the concept of the steady-state simulation, of both variables, being statistically equivalent to the historical ones at all time scales including the large scale, annual and over-annual, in which the Hurst–Kolmogorov behaviour dominates.

2. Description of data

Wind speed and sunshine duration records used in the analysis were retrieved from measuring stations whose data are available online. The criteria for station selection were:

a) A minimum acceptable record length of 70 years so as the Hurst coefficient to be estimated with some accuracy.
b) The existence of metadata related to wind speed data and especially information about the measurement height above ground.
c) A maximum number of three homogeneous periods, in each of which the measurement height above ground is constant (stations with too frequent changes may not be reliable).

However, records of this time length are rare worldwide. In particular, in some continents (Asia, Africa) there is lack of data series of this length. Even in Europe and North America most of the free access records refer to a period of 50 years or less. Furthermore, there is total lack of long solar radiation records. However, this variable can be indirectly estimated by sunshine duration [37].

After an extensive search, wind speed and sunshine duration records fulfilling these criteria were retrieved exclusively from European databases, the KNMI Climate Explorer, the European Climate Assessment & Data (ECA&D) and the Deutscher Wetterdienst databases. A total number of 20 wind speed records and 21 sunshine duration records were found. In addition, wind speed time series from Dublin Airport and Valentia stations were found from the website of the Irish Meteorological Service in chart form and were digitized using the Engauge software. The data retrieved consist of daily records except for the ones of the Irish stations whose records are annual averages. In Tables 1 and 2 stations details are shown.

As known, wind speed at a certain site increases with height and thus, the analysis of wind speed time series requires a single measurement height above ground during the time period of operation. However, the collected daily time series do not refer to a single height above ground due to changes of the observation height at certain time periods in measuring stations. Based on the assumption of process stationarity, this problem was overcome by modifying the data of all the time periods except for the last period of records for each station so as to refer to a unified altitude (data homogenization). Specifically the following procedure was applied:

a) The daily time series were grouped to time periods where the measurement height above ground is constant.