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Comparison between the bivariate Weibull probability approach and linear regression for assessment of the long-term wind energy resource using MCP

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ABSTRACT

A detailed investigation of a measure–correlate–predict (MCP) approach based on the bivariate Weibull (BW) probability distribution of wind speeds at pairs of correlated sites has been conducted. Since wind speeds are typically assumed to follow Weibull distributions, this approach has a stronger theoretical basis than widely used regression MCP techniques. Building on previous work that applied the technique to artificially generated wind data, we have used long-term (11 year) wind observations at 22 pairs of correlated UK sites. Additionally, 22 artificial wind data sets were generated from ideal BW distributions modelled on the observed data at the 22 site pairs. Comparison of the fitting efficiency revealed that significantly longer data periods were required to accurately extract the BW distribution parameters from the observed data, compared to artificial wind data, due to seasonal variations. The overall performance of the BW approach was compared to standard regression MCP techniques for the prediction of the 10 year wind resource using both observed and artificially generated wind data at the 22 site pairs for multiple short-term measurement periods of 1–12 months. Prediction errors were quantified by comparing the predicted and observed values of mean wind speed, mean wind power density, Weibull shape factor and standard deviation of wind speeds at each site. Using the artificial wind data, the BW approach outperformed the regression approaches for all measurement periods. When applied to the real wind speed observations however, the performance of the BW approach was comparable to the regression approaches when using a full 12 month measurement period and generally worse than the regression approaches for shorter data periods. This suggests that real wind observations at correlated sites may differ from ideal BW distributions and hence regression approaches, which require less fitting parameters, may be more appropriate, particularly when using short measurement periods.

1. Introduction

The installed capacity of wind energy systems has seen rapid growth over the last decade [1] as governments, businesses and individuals seek to reduce their carbon emissions in response to growing concern over climate change. In the UK, where a legally binding commitment exists to reduce CO_2 equivalent emissions by 80% in 2050 compared to 1990 levels, wind power is considered a key part of the Government's strategy to decarbonise electricity supplies [2]. To maximise the UK's favourable wind potential, wind energy systems on a range of scales should be utilised.

Vital to the successful deployment of wind power systems on any scale is an accurate assessment of the available wind energy resource. Since wind flows are stochastic in nature, the wind resource must be characterised using long-term averages which describe the available power at the proposed (target) site. For large-scale installations, this typically involves onsite measurements of wind speed and direction covering 1–3 years [3], in addition to long-term correlation with a nearby reference site to account for inter-annual variations. The correlation is achieved using one of a family of approaches known collectively as measure–correlate–predict (MCP). A typical MCP approach involves using regression or other techniques to relate wind speed measurements at a target site with concurrent measurements at a nearby reference site [4], or with appropriate atmospheric data from reanalysis projects [5]. Long-term historical reference data is then used with the

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established relationship to predict the long-term wind resource at the target site.

For small-scale installations, a long-term measurement campaign may not be practical or financially viable and developers may rely on wind maps, empirical correction factors [6] or boundary layer scaling approaches [7,8]. MCP applied to very short-term measurement periods may also be a viable approach [9] providing the performance of the techniques as a function of the measurement period has been investigated.

The literature related to MCP is extensive, encompassing industry reports, commercial software, and conference and academic papers dating back to the 1940s [10]. Here we mention only the major classes of MCP techniques, a more detailed review can be found in Ref. [10]. Early MCP approaches [11,12] involved simple scaling of the short-term mean wind speed using long-term reference site measurements, thus providing only limited information regarding the long-term wind resource. Later studies [4,13–15] used linear regression of the scalar wind speeds at the target and reference sites to predict a long-term time series based on short-term measurements, from which, parameters related to the wind speed distribution could be estimated. More complex regression models, including two-dimensional [16], vector [14] and non-linear [17] have also been investigated. Mortimer [18] proposed binning wind data according to the reference site wind speed and direction and construction of a matrix containing ratios of the short-term reference and target site wind speeds. The ratios were used along with a matrix of standard deviations to predict the long-term target site wind speeds. A matrix approach was also proposed by Woods and Watson [19] where wind data was binned according to reference and target site wind direction. Further processing was undertaken to account for the directional wind veer that may occur in complex terrain. Learning based techniques such as artificial neural networks (ANNs), which represent learned patterns between input and output data by weighted interconnections, are increasingly being applied to MCP [20–24]. Given training data with known reference and target site wind speeds, the patterns can be learnt and applied to unseen data to make predictions at the target site. MCP approaches based on the joint probability distribution function (pdf) between reference and target site wind speeds have also been proposed [25,26], although such approaches have received relatively little attention considering their attractive theoretical properties. Despite the variety of proposed approaches, MCP implementation in commercial software packages [27–29] is often restricted to top-down linear regression or scaling approaches, presumably due to their simplicity and empirical success.

This study is concerned with an MCP approach based on the joint pdf between the reference and target site wind speeds. The motivation for this approach is that whilst simple linear regression techniques are based on the assumption of a bivariate Gaussian distribution between two variables [26,30], univariate Weibull distributions are typically used in wind resource assessment [31]. Hence there is a stronger theoretical justification for describing the correlation between target and reference site wind speeds using a bivariate Weibull (BW) distribution. Such an approach provides a direct mathematical basis for modelling the distribution of wind speeds at the target site given a specific input wind speed at the reference site. The modelled distributions are known as conditional distributions since they are conditional on the input reference site wind speed. This approach contrasts with regression techniques which treat the conditional distributions as scatter or residual errors about a true mean value. Recently, Perea et al. [26] used artificially generated wind speed data to investigate the utility of an MCP approach based on BW probability distributions. Their results indicated that the approach performed better than several established MCP techniques. However, a vital question is whether such a promising approach can be successfully applied to real wind speed observations which will likely deviate from idealised BW distributions and which may contain terms dependent on season and wind angle.

In this work, the BW approach is applied to wind speed observations at 22 pairs of UK sites located in a variety of terrains, in addition to artificially generated wind data drawn from ideal BW distributions. A sliding window technique is applied to data records covering 11 years, using short-term measurement periods of 1–12 months, to predict the long-term (10 year) wind resource at each site. The accuracy of the wind resource predictions is assessed through a variety of error metrics and the results compared to widely used regression MCP approaches. The aims of this work are: (I) To investigate the practical challenges of applying the BW approach to real wind data compared to artificial data drawn from ideal BW distributions, (II) To compare the performance of the BW approach with widely used linear MCP techniques using real wind data from a number of sites.

2. Methodology

MCP approaches are generally concerned with predicting a long-term historical time-series of wind speeds (and possibly directions) using short-term concurrent wind measurements at a correlated reference/target site pair. The short-term measurements are used to model the relationship between the two sites, while long-term historical reference data are used as model inputs to predict the long-term target site wind speeds.

Using simple linear regression, any input reference site wind speed has a corresponding single-valued output prediction at the target site. Repeating this process for the full historical time-series at the reference site produces an estimated long-term historical time series at the target site that is assumed to be a suitable predictor of the future wind resource. The BW probability approach involves a similar process but with the following distinctions. Firstly, the BW approach seeks to directly model the underlying distribution of target site wind speeds rather than the historical time-series. Secondly, rather than the restriction that a specific reference site wind speed corresponds to a specific target site wind speed, the BW approach predicts a distribution of target site wind speeds for every reference site wind speed in the form of a conditional probability distribution. Since wind power is proportional to the cube of the wind speed, these characteristics are important in achieving accurate wind resource predictions. The BW approach will now be described in more detail.

2.1. A bivariate probability approach to MCP

Given two correlated random variables, their relationship may be described by a bivariate pdf. The height of the pdf surface at a point describes the probability of observing a particular combination of variable pairs. The distribution can be thought of as being composed of a series of one-dimensional, conditional probability distributions or vertical slices through the two-dimensional probability surface. Each slice describes the probability of observing particular values of one variable given a fixed value of the second. In addition, the conditional probability slices can be integrated across one of the variables to yield the marginal, or complete, distribution of the other variable.

For wind speeds observed at a correlated reference/target site pair, the conditional and marginal probability densities have a direct physical interpretation. The conditional probability density is given by [26]: