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Long-term wind resource assessment for small and medium-scale turbines using operational forecast data and measure–correlate–predict

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Output from a state-of-the-art, 4 km resolution, operational forecast model (UK4) was investigated as a source of long-term historical reference data for wind resource assessment. The data were used to implement measure–correlate–predict (MCP) approaches at 37 sites throughout the United Kingdom (UK). The monthly and hourly linear correlation between the UK4-predicted and observed wind speeds indicates that UK4 is capable of representing the wind climate better than the nearby meteorological stations considered. Linear MCP algorithms were implemented at the same sites using reference data from UK4 and nearby meteorological stations to predict the long-term (10-year) wind resource. To obtain robust error statistics, MCP algorithms were applied using onsite measurement periods of 1–12 months initiated at 120 different starting months throughout an 11 year data record. Using linear regression MCP over 12 months, the average percentage errors in the long-term predicted mean wind speed and power density were 3.0% and 7.6% respectively, using UK4, and 2.8% and 7.9% respectively, using nearby meteorological stations. The results indicate that UK4 is highly competitive with nearby meteorological observations as an MCP reference data source. UK4 was also shown to systematically improve MCP predictions at coastal sites due to better representation of local diurnal effects.

1. Introduction

Small and medium-scale wind turbines, typically defined as <500 kW rated power [1,2], have exciting prospects as we move towards a low carbon energy future. As a source of renewable, low carbon energy, such turbines have the potential to contribute to both carbon savings and improved diversity of supply. The global market has seen rapid growth in the last decade with an increase in capacity of 18% reported for 2012, compared to the previous year [1]. Within the UK, the small and medium-scale wind energy industry is predicted to contribute £241 million Gross Value Added (a measure of the contribution of an individual market sector) to the UK economy in 2014. While changes to the UK Feed-in Tariff have slowed growth since 2013, the industry has the potential to contribute up to £864 million to the UK economy in 2023, given appropriate political support [2]. However, in order for small and medium-scale wind energy to continue to flourish, methods for rapid, accurate and low-cost wind resource assessment are required [1].

In the large-scale wind energy industry, estimates of the long-term wind resource are generally achieved using the measure–correlate–predict (MCP) method [3]. In a typical MCP approach, short-term wind data are obtained at the location and height of the potential wind turbine site (target site) over a training period and these data are correlated to a nearby reference site where a long-term historical data record is available. The correlated data are then used to make a long-term prediction at the target site, under the assumption that the historical wind resource is an adequate predictor of the future resource.

The length of the short-term measurement period and long-term prediction period will vary depending on the size of the project and the rigour of the site assessment procedure. For large-scale wind projects, onsite measurement periods of 1–3 years are generally required along with long-term prediction over several

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decades [3,4]. For small and medium-scale installations, the lower investment costs may justify shorter measurement and prediction periods, reflecting the reduced financial risk [5]. In many cases, long-term reference data are sourced from established monitoring stations operated, for example, by national meteorological institutions or airports. However, in recent years there has been increasing interest in the use of output from numerical weather prediction (NWP) models, as well as derived atmospheric reanalysis data sets, as a source of long-term reference data for MCP [6]. Both NWP and reanalysis involve the assimilation of large amounts of data including observations from satellites, weather balloons, aircraft, ships, buoys and surface meteorological stations. These data are used to initialise numerical models which produce a time-evolving, three-dimensional grid of modelled atmospheric variables [6]. Reanalysis data are so termed because they represent a second analysis, using a consistent assimilation and analysis model, as well as incorporation of observations not available to real-time operational forecasts [7].

Such data are attractive in that (i) they are available globally and (ii) compared to nearby surface wind observations, they may be less affected by changes in land-use and local obstructions, and they may also cover a longer historical period.

While these data are increasingly being used in long-term wind resource assessment [8], there are relatively few rigorous studies considering the suitability of NWP and derived data sets in MCP applications. Brower [6] carried out a detailed study using NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) [7] reanalysis as an MCP reference data source for sites located in the United States. It was found that in some cases, reanalysis data can be subject to spurious trends and internal inconsistencies, particularly when considering data lengths of greater than 10 years. Liléo and Petrick [9] compared NCEP/NCAR with MERRA [10] (Modern Era Retrospective Analysis for Research) as well as a more recent NCEP release NCEP/CFSR (Climate Forecast System Reanalysis) [11], with improved spatial and temporal resolution, using observations at 24 meteorological stations in Sweden. Their results indicated that MERRA performed better in MCP analysis, due to the data's higher spatial and temporal resolution, and was less prone to the spurious trends observed in other reanalysis data. Similar studies have also been reported by Pinto et al. [12] as well as Jimenez et al. [13]. The emerging picture from these preliminary studies is that data sets with high spatial and temporal resolution are required for the successful implementation of MCP and that long-term inconsistencies may affect predictions on time-scales greater than 10 years. Since reanalysis data generally have low spatial resolution (tens to hundreds of kilometres), and variable temporal resolution, this presents a challenge to their use in MCP.

One possible solution is the use of mesoscale models with improved spatial and temporal resolution driven either by reanalysis or some alternative data containing consistent observations of atmospheric variables [14]. Operational forecast data from high resolution NWP models may be considered as a natural choice in this regard. Since forecast data can be obtained at the location of the target sites (subject to the model resolution), the data may offer improved representation of localised climates compared to nearby surface measurements located tens of kilometres away, or low resolution reanalysis data. Currently, there is a lack of rigorous studies investigating the use of high resolution, operational forecast data in MCP. In this study, the Met Office Unified Model (UM) is investigated as an MCP reference source in the context of small and medium-scale wind installations.

The UM [15] is a state-of-the-art operational weather and climate forecast system, used for both global and regional prediction. It is currently operated with horizontal grid spacings of approximately 25 km globally and 1.5 km (previously 4 km) within the UK. As a terrain-following, mesoscale model, the UM is capable of producing, local, site-specific forecasts through progressively higher resolution models whose boundary conditions are provided by the global model. Wilson and Standen [16] recently demonstrated that due to the higher spatial and temporal resolution of the 4 km model (UK4), the data are capable of outperforming reanalysis in wind resource assessments using downscaling methods.

In the current study, UK4 is investigated as a source of long-term reference data for MCP and its performance is compared with alternative reference data obtained from nearby meteorological stations. Linear MCP approaches are used to predict the long-term (10 year) wind resource at 22 target sites (later extended to 37) located in four different terrain types. A range of error metrics are used to compare the accuracy of the predictions using the two sources of reference data. The study is particularly relevant to small and medium-scale wind resource assessment due to the range of heights considered (10–22.5 m above ground level) and the length of the long-term predictions (10 years). The main objectives of the study are (i) to investigate the utility of using UK4 data as a long-term reference data source for MCP, (ii) to determine the most appropriate forecast height to use in this context, and (iii) to investigate factors that may impact the performance of UK4 within the MCP approach, including local terrain and the use of hindcast data.

2. Methodology

2.1. MCP algorithms

A large range of MCP approaches have been investigated in a research context. These include two-dimensional, vector and non-linear regression techniques [17–20], matrix approaches [21,22] and more recently, artificial neural networks [23–25] and joint probability distributions [26–28]. A recent review by Carta et al. [3] considered over 150 studies demonstrating the wide range of available techniques. Despite the large number of alternatives, linear approaches [29,30] are currently the most widely used in the wind industry, presumably due to their simplicity and effectiveness [3]. The current study is concerned with investigating the utility of operational forecast data as an MCP reference data source, rather than investigating specific MCP algorithms. Hence, two established linear MCP approaches are used in this work, as described below.

2.1.1. Linear regression

In a linear regression approach, the target and reference site wind speeds may be related by the linear expression:

$$\widehat{u}_{tar} = \alpha + \beta u_{ref} + \varepsilon \quad (1)$$

where $\widehat{u}_{tar}$ is the predicted wind speed at the target site, u_{ref} is the observed wind speed at the reference site, α and β are the regression coefficients obtained using a least squares fit to the training data and ε is an error term which represents the residual scatter.

Previous studies [5,28] have indicated that ε can be modelled using a zero mean Gaussian distribution of the form:

$$\varepsilon = N\left(0, \sigma_{res}^2\right) \quad (2)$$

where σ_{res} is the sample standard deviation of the residuals about the predicted target site wind speeds $\widehat{u}_{tar}$, as calculated from the N training observations using [31]: