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Using reanalysis data to quantify extreme wind power generation statistics: A 33 year case study in Great Britain

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A B S T R A C T

With a rapidly increasing fraction of electricity generation being sourced from wind, extreme wind power generation events such as prolonged periods of low (or high) generation and ramps in generation, are a growing concern for the efficient and secure operation of national power systems. As extreme events occur infrequently, long and reliable meteorological records are required to accurately estimate their characteristics.

Recent publications have begun to investigate the use of global meteorological "reanalysis" data sets for power system applications, many of which focus on long-term average statistics such as monthly-mean generation. Here we demonstrate that reanalysis data can also be used to estimate the frequency of relatively short-lived extreme events (including ramping on sub-daily time scales). Verification against 328 surface observation stations across the United Kingdom suggests that near-surface wind variability over spatiotemporal scales greater than around 300 km and 6 h can be faithfully reproduced using reanalysis, with no need for costly dynamical downscaling.

A case study is presented in which a state-of-the-art, 33 year reanalysis data set (MERRA, from NASA-GMAO), is used to construct an hourly time series of nationally-aggregated wind power generation in Great Britain (GB), assuming a fixed, modern distribution of wind farms. The resultant generation estimates are highly correlated with recorded data from National Grid in the recent period, both for instantaneous hourly values and for variability over time intervals greater than around 6 h. This 33 year time series is then used to quantify the frequency with which different extreme GB-wide wind power generation events occur, as well as their seasonal and inter-annual variability. Several novel insights into the nature of extreme wind power generation events are described, including (i) that the number of prolonged low or high generation events is well approximated by a Poission-like random process, and (ii) whilst in general there is large seasonal variability, the magnitude of the most extreme ramps is similar in both summer and winter.

An up-to-date version of the GB case study data as well as the underlying model are freely available for download from our website: http://www.met.reading.ac.uk/~energymet/data/Cannon2014/.

1. Introduction

Due to the increasing market penetration of wind power, extreme wind power generation events (such as prolonged periods of low generation and ramps in generation) are of growing concern to policy makers and transmission system operators. Widespread low (or high) power generation can persist because wind turbines are insensitive to changes in wind speed when it is low (and turbines produce little or no net power), or high (and turbines produce their rated maximum power). Such persistent events have important implications for electricity system capacity adequacy [1], as well as for wider energy system planning and strategic assessment purposes. In the near future, persistent (multi-day) low generation events will likely influence fuel reserve planning (especially for natural gas), whilst in the longer term, quantifying their frequency and severity will be essential for assessing the potential of innovative technologies such as bulk energy storage [2]. Ramps in

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generation often occur at moderate wind speeds where turbine output ranges from zero to a rated maximum power. They also occur at extremely high wind speeds when turbines are shut down for safety, though this is much rarer [3,4]. Such ramps in generation provide challenges for transmission system operators, who schedule reserve holding in advance and require long term strategies for system balancing [5].

Assessing the frequency of extreme generation events directly from power system data is problematic as there is too little data available to determine representative return periods for events that recur infrequently [6]. This is because wind speeds vary on inter-annual and inter-decadal time scales [7,8]. In addition, the geographical distribution of wind farms is constantly changing. In Great Britain (GB), there has been a considerable shift towards wind farms located in the south and offshore. For this reason, weather events that occurred only a few years ago may not have the same impact on the current wind farm distribution as they did before. In response to these challenges, recent studies have estimated the statistical behaviour of the wind resource by inferring the long-term nationally-aggregated wind power output from surface-based wind speed observations. For example [3,9], estimated long-term mean generation statistics for the United Kingdom (UK) and GB respectively, including a brief analysis of low wind periods. Recent studies such as [4,10,11] have also used surface observations to estimate generation statistics.

As an alternative to surface-based observations, authors in academia [12–14], government [1] and industry [15] have begun investigating the potential usefulness of meteorological reanalysis data. Modern "reanalyses" are constructed using global numerical weather prediction models that assimilate observations from a wide variety of sources including land surface stations, buoys, radiosonde balloons, aircraft and satellites [16,17]. Reanalysis data is, by construction, coarsely resolved and so cannot represent small-scale wind fluctuations at a particular site [18]. Nevertheless, as will be shown in Section 2, good agreement with surface-based observations is found when considering variability over sufficiently large spatiotemporal scales.

For assessing wind power variability on a multi-hour, regionally-aggregated scale (as is the focus here), reanalyses may offer numerous advantages over surface-based observations. Firstly, wind observations are heavily influenced by their immediate locale (local topography, vegetation or buildings), and so may not accurately represent the conditions at nearby wind farms. In contrast, because reanalyses do not resolve these local features, they reproduce the large scale wind variability more faithfully. Secondly, changing measuring equipment and recording standards produce biases and discontinuities in the observational record. The impact of these biases on reanalysis data is reduced by the use of multiple observation sources, and by the consistent modelling (and data assimilation) methods used throughout [16,17]. Thirdly, there are few surface-based observations offshore, whereas reanalysis data has global coverage. Finally, modern reanalysis products estimate the wind at multiple vertical levels near the surface using atmospheric boundary layer parameterisations. Whilst still heavily idealised, their consideration of stability effects on the wind profile represents an improvement over the assumption of a neutrally-stratified boundary layer, which is implicit in most studies using surface-based wind observations [4,10,11].

1.1. Paper outline

This paper is divided into two main parts (Sections 2 and 3). Section 2 begins by investigating the accuracy with which data from the MERRA reanalysis [16] reproduces the observed variability in near-surface wind speed (Sections 2.1–2.2) and aggregated wind power generation (Section 2.3) over different spatiotemporal scales. Statistics of long-term mean aggregated wind power and extreme events are then derived and compared to available power system data (Sections 2.4–2.5).

In Section 3, a 33 year climatology of GB-aggregated wind power generation from 1980 to 2012 is used to estimate the frequency of extreme events (persistent low or high generation and ramping), assuming the wind farm distribution of September 2012 (Section 3.1). The inter-annual and seasonal variability of the results is examined (Sections 3.2–3.3), as well as the sensitivity to changes in the assumed dependence of wind farm power generation on wind speed (herein, the "power curve"; Section 3.4).

Conclusions are presented in Section 4, where the potential impacts of the climatology for power system management are discussed.

2. Reanalysis verification

2.1. 10 m altitude wind speed comparisons

The degree to which wind speeds in MERRA reproduce surface-based, hourly, 10 m altitude UK wind observations from the MIDAS archive [19] will now be evaluated.[1] To facilitate a proper comparison, the gridded MERRA data was bi-linearly interpolated to obtain wind speeds at the co-ordinates of all 328 MIDAS stations. Overall, the MIDAS observations span 1980–2011, though no individual stations were operational for all 32 years.

Fig. 1(a) shows a site by site comparison between the 10 m altitude wind speed records in MERRA (V) and MIDAS (U). As [14] similarly noted, whilst in most cases MERRA accurately reproduces the MIDAS wind speeds (the correlation coefficient is 0.73), there is a small systematic overestimation for around $U < 6$ ms^{-1} and a large underestimation for around $U > 20$ ms^{-1}. The worst underestimations are removed when stations above 300 m altitude are discounted (Fig. 1(b)). This is a result of the smoothed topography used in MERRA,[2] which leads to artificially low wind speeds for stations residing on the (unresolved) peaks [20]. The smoothed topography may similarly contribute to the small overestimation in wind speed for some low altitude stations.

Although MERRA cannot fully capture the observed MIDAS wind variability at individual locations, the mean wind speed (spatially averaged over all stations) is reproduced more accurately (Fig. 1(c)). The range of mean wind speeds is smaller than at individual sites, reflecting the reduced influence of extremely high winds which only simultaneously effect a small number of stations. The correlation coefficient between the mean wind speeds in MERRA and MIDAS is greatly increased (to 0.94), which is consistent with the "smoothing" commonly observed when averaging (or aggregating) over large numbers of stations [3,21]. This smoothing reduces the impact of small-scale wind variability, leaving the large-scale variability (well resolved by MERRA) dominant. The improved agreement in mean wind speed implies that MERRA should be considerably more successful in reproducing regionally-aggregated generation than that of an individual wind farm.

To evaluate the degree to which MERRA reproduces the temporal variability observed in MIDAS, the above analysis was repeated for the change in wind speed over different time spans. At individual locations, MERRA tends to underpredict the change in wind speed relative to MIDAS on short time spans (Δt = 3 hr,

[1] The MIDAS wind speed observations are not assimilated into MERRA.

[2] The smoothed topography in MERRA is a result of the coarse (approximately 50 km × 50 km) horizontal grid used in the underlying numerical weather prediction model.