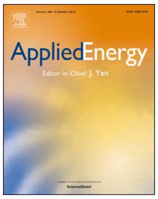
Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



A boundary layer scaling technique for estimating near-surface wind energy using numerical weather prediction and wind map data

D.J. Allen[a,b], A.S. Tomlin[b,*], C.S.E. Bale[b,c], A. Skea[d], S. Vosper[d], M.L. Gallani[d]

[a] *Doctoral Training Centre in Low Carbon Technologies, School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK*
[b] *School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK*
[c] *Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*
[d] *Met Office, Fitzroy Road, Exeter EX1 3PB, UK*

HIGHLIGHTS

- Improved accuracy of wind speed predictions from a boundary layer scaling technique.
- Highly accurate power density predictions from numerical weather prediction data.
- Boundary layer scaling more suitable for wind speed prediction than mandated method.
- Robust wind resource assessment techniques for near-surface wind speeds.

ARTICLE INFO

Keywords:
Near-surface wind
Wind resource assessment
Small and medium scale wind turbine
Boundary layer scaling
Numerical weather prediction

ABSTRACT

A boundary layer scaling (BLS) method for predicting long-term average near-surface wind speeds and power densities was developed in this work. The method was based on the scaling of reference climatological data either from long-term average wind maps or from hourly wind speeds obtained from high-resolution Numerical Weather Prediction (NWP) models, with case study applications from Great Britain. It incorporated a more detailed parameterisation of surface aerodynamics than previous studies and the predicted wind speeds and power densities were validated against observational wind speeds from 124 sites across Great Britain. The BLS model could offer long-term average wind speed predictions using wind map data derived from long-term observational data, with a mean percentage error of 1.5% which provided an improvement on the commonly used NOABL (Numerical Objective Analysis of Boundary Layer) wind map. The boundary layer scaling of NWP data was not, however, able to improve upon the use of raw NWP data for near surface wind speed predictions. However, the use of NWP data scaled by the BLS model could offer improved power density predictions compared to the use of the reference data sets. Using a vertical scaling of the shape factor of a Weibull distribution fitted to the BLS NWP data, power density predictions with a 1% mean percentage error were achieved. This provided a significant improvement on the use of a fixed shape factor which must be utilised when only long-term average wind speeds are available from reference wind maps. The work therefore highlights the advantages that use of a BLS model for wind speed and NWP data for power density predictions can offer for small to medium scale wind energy resource assessments, potentially facilitating more robust annual energy production and financial assessments of prospective small and medium scale wind turbine installations.

1. Introduction

National governments across the world are attempting to decarbonise their electricity supplies as part of their efforts to meet CO_2 emission reduction targets and mitigate the risks of climate change [1]. As part of this action, national governments have committed to ambitious renewable energy generation targets. The European Union (EU) has set a target of providing 50% of total electricity supply from renewable energy generating sources by 2030, while China and Australia have committed to 35% and 23.5% of total electricity being supplied by renewable energy generation by 2020 respectively [1]. As part of the EU's renewable energy generation commitment, the UK government committed to a legally binding target to provide 15% of its total energy from renewable sources by 2020 [2]. Meeting these targets requires a

---

[*] Corresponding author.
E-mail address: A.S.Tomlin@leeds.ac.uk (A.S. Tomlin).

http://dx.doi.org/10.1016/j.apenergy.2017.09.029
Received 10 May 2017; Received in revised form 31 August 2017; Accepted 9 September 2017
0306-2619/

Please cite this article as: Allen, D.J., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.09.029

transition of energy systems across the world from fossil-fuel based to low-carbon electricity sources. Microgeneration technologies such as small scale wind turbines, which are installed to provide energy for a single home or a community [3], can play a key role in energy systems transition [4]. The UK has one of the highest wind resource potentials in Europe [5] and therefore wind power, including small and medium wind energy, will be a key component in the UK's energy system transition.

Microgeneration technologies are costly to install and therefore to promote microgeneration uptake, a financial subsidy is typically required to stimulate deployment [4]. In some countries, a Feed-in Tariff (FIT) has been introduced to provide this financial subsidy to microgeneration installers [6–10]. For example, in the UK, a FIT was introduced in 2010 to provided financial incentives for each kilowatt-hour of electricity generated by microgeneration technologies, including wind turbines, installed in England, Wales or Scotland [11]. Similar schemes have been deployed in other countries with particular success in terms of uptake achieved in Germany [9]. However, even with financial subsidies, and indeed to optimise the returns from these, microgeneration technologies must be sited in locations where there is sufficient resource to ensure that each installation is financially viable. This is particularly relevant for small and medium wind turbines as wind resource is highly variable, both spatially and temporally [12,13]. Small and medium wind turbines utilise near-surface winds, defined as wind at the lowest level of the boundary layer, close to the surface of the Earth [13], to generate electricity. Near-surface winds are typically monitored at 10 m above ground level [14], although turbine hub heights could be higher than this for medium scale wind turbines. Therefore, any wind resource assessment for small and medium wind turbines must estimate near-surface winds. In this study, the accuracy of wind resource estimation methodologies for near-surface wind speeds were investigated, using sites in Great Britain as a case study.

For small and medium wind turbines, where the overall investment potentially is much lower than for large wind farms, a wind resource assessment method is required at the initial project stage which is quick to deploy and economically viable [15]. It must, however, still be rigorous enough to ensure that the estimated annual energy production is accurate, providing the turbine installer with sufficient confidence to either move forward with the installation, or to justify further project costs for a more in-depth wind resource characterisation. For such turbines, on-site anemometry conducted over a number of years to capture all temporal variability in a site's wind resource is not practicable due to the timescales and costs associated [15]. In the absence of on-site measurements, alternative methodologies to assess wind resource availability at initial project stages are required. A desk study is usually undertaken at this stage [16] and at a minimum, should provide an accurate prediction of average hub height wind speed and power density in the wind flow, from which the annual energy production of the wind turbine can be estimated [15]. Power density describes the energy per unit area in the wind flow and is calculated based upon the estimated wind speed frequency distribution at a particular site [15].

An initial assessment of near-surface wind resource can be conducted using numerous methods [7,17–20]. Near-surface wind speed estimations can be produced through the vertical and horizontal scaling of available reference wind data which will vary in terms of spatial and temporal resolution, depending on location. A commonly available source of reference data is reanalysis wind data, including the Modern Era Retrospective-Analysis for Research and Applications (MERRA) data set [7,20]. Weather forecasting data however, tends to be higher resolution and could be available from national meteorological centres or from the Weather Research and Forecasting (WRF) model [19]. Typical methods for using such data sets include the application of a Kalman filter to a time-series of Numerical Weather Prediction (NWP) wind data [18] or through scaling methods. Examples of each of these approaches have been used to estimate near-surface wind speeds for grid squares, sized at around 1 km using NWP data, up to 30 km for studies utilising WRF data [19]. For small and medium wind turbines, which require accurate estimation of the spatially variable wind resource, coarser spatial resolutions may be insufficient to provide an accurate wind resource estimation at a specific location. A previous study has analysed the coupling of a meso-scale model using WRF and the Wind Atlas Analysis and Application Program (WAsP) micro-scale model to estimated wind speed at 60 m on a higher spatial resolution [17]. However, the cost of the WAsP micro-scale modelling technique, typically the purchasing of the license [21], is likely to be prohibitive at the initial stages of a small and medium wind turbine project, due to lower project budgets. While these wind resource assessment techniques predict hourly wind speeds, it is argued here that for small and medium wind turbines, at the initial scoping stage of the project, only a demonstration of technical viability using a long-term average wind speed is required. Once a site's viability has been established using this long-term average wind speed, wind resource assessment techniques which forecast hourly wind speeds, can be implemented to fully characterise a site's wind resource at later project stages.

A quick, lost cost yet effective assessment of the long-term average wind speed of a proposed site for a small and medium wind turbine is therefore required. For all wind turbines under 50 kW to receive payments under the British FIT, a wind resource estimation technique prescribed within the FIT accreditation process must also be completed [22]. The Microgeneration Certification Scheme (MCS) methodology is described as a "*method using freely available wind speed data (NOABL) and simple tabulated correction factors for the local terrain, obstructions and turbine height*" [22]. The results of this methodology must be presented to potential wind turbine adopters with equal prominence compared to other more detailed wind resource assessment techniques conducted during the initial stages of the project [22]. Given its use of "simply tabulated correction factors", the suitability of the MCS method to provide an accurate long-term average wind speed prediction for reliable annual energy production estimates should be questioned.

A boundary layer scaling technique (BLS) for near-surface wind speed prediction has been developed by the Met Office [23] and refined by Weekes [15]. A BLS model applies a number of correction factors to a reference wind climatology, based on the surface characteristics of a site such as vegetation, buildings and surface morphology. Surface characteristics are parameterised into surface roughness values, describing the frictional effects of obstacles at the surface on wind flow momentum [23]. The role of surface roughness parameterisation in wind resource assessments is particularly important for near-surface wind predictions, which are more affected by surface drag than winds higher in the atmosphere [13]. The BLS and MCS models can be utilised to provide quick and cheap estimations of long-term average near-surface hub height wind speed.

Within Great Britain, two reference wind climatologies, in the form of wind maps, which provide long-term average wind speeds are available; the Numerical Objective Analysis of Boundary Layer (NOABL) [24] and the National Climatic Information Centre (NCIC) data sets [25]. From these average wind speeds, power density cannot be directly estimated since a frequency distribution is not provided. However, the use of a fixed Weibull shape factor to represent a wind speed distribution from which power density can be estimated has been suggested [23]. However, both power density and average wind speed can also be estimated from the hourly time-series of wind speeds available from NWP data, where available. NWP wind speed data was provided for this study by the Met Office from their UK4 and UKV NWP models [26]. The availability of these different reference wind climatologies allowed the accuracy of both wind speed and power density predictions to be analysed in this study. To provide wind speed predictions appropriate for the chosen wind turbine installation, reference wind climatologies must be scaled to the hub height of the proposed wind turbine. Wind map data was only available at the heights of 10 m, 25 m and 45 m [24,25]. Raw NWP data was available at several heights from the forecast model output, but must be scaled to provide near-