J. Wind Eng. Ind. Aerodyn. 115 (2013) 104–111

Contents lists available at SciVerse ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Estimating the potential yield of small wind turbines in urban areas: A case study for Greater London, UK

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ARTICLE INFO

Article history:
Received 16 July 2012
Received in revised form
14 January 2013
Accepted 26 January 2013
Available online 28 February 2013

Keywords:
Wind
Energy
Micro-generation
Urban
Boundary layer
Roughness length
Morphology

ABSTRACT

To optimise the placement of small wind turbines in urban areas a detailed understanding of the spatial variability of the wind resource is required. At present, due to a lack of observations, the NOABL wind speed database is frequently used to estimate the wind resource at a potential site. However, recent work has shown that this tends to overestimate the wind speed in urban areas. This paper suggests a method for adjusting the predictions of the NOABL in urban areas by considering the impact of the underlying surface on a neighbourhood scale. In which, the nature of the surface is characterised on a 1 km^2 resolution using an urban morphology database.

The model was then used to estimate the variability of the annual mean wind speed across Greater London at a height typical of current small wind turbine installations. Initial validation of the results suggests that the predicted wind speeds are considerably more accurate than the NOABL values. The derived wind map therefore currently provides the best opportunity to identify the neighbourhoods in Greater London at which small wind turbines yield their highest energy production. The model does not consider street scale processes, however previously derived scaling factors can be applied to relate the neighbourhood wind speed to a value at a specific rooftop site.

The results showed that the wind speed predicted across London is relatively low, exceeding 4 ms^{-1} at only 27% of the neighbourhoods in the city. Of these sites less than 10% are within 10 km of the city centre, with the majority over 20 km from the city centre. Consequently, it is predicted that small wind turbines tend to perform better towards the outskirts of the city, therefore for cities which fit the Burgess concentric ring model, such as Greater London, 'distance from city centre' is a useful parameter for siting small wind turbines. However, there are a number of neighbourhoods close to the city centre at which the wind speed is relatively high and these sites can only been identified with a detailed representation of the urban surface, such as that developed in this study.

1. Introduction

To reduce the carbon emissions associated with the electricity delivered to the built environment, the UK government has developed a number of schemes to incentivise the growth of micro-generation technologies, including the Low Carbon Buildings Programme, the Code for Sustainable Homes and the Feed-in tariffs Order (Allen et al., 2008; Walker, 2011). As a result there has been an increase in the number of micro-generation technology installations in the UK, including micro-wind turbines (Bergman and Jardine, 2009; RenewableUK, 2010). However, a number of high profile field studies have shown that currently, small wind turbines installed in urban areas in the UK generally produce less energy than expected prior to installation. This has raised doubts about their potential, both in the context of the financial benefits to the owner and with respect to decarbonising the UK energy supply (Encraft, 2009; James et al., 2010).

The literature suggests the reason for the poor performance is twofold: firstly, the majority of the turbines installed in urban areas are designed without taking into account the complex nature of the wind resource at roof level. Consequently, a number of recent studies have focused on designing wind turbines specifically for urban applications (Booker et al., 2010; Henriques et al., 2009; Muller et al., 2009). Secondly, due to the difficulty estimating the wind resource in an urban area there has been poor placement of the turbines. To optimise the placement of the turbines an accurate method of assessing the variability of the wind resource across a wide urban area is required.

For large-scale wind turbine installations extensive wind monitoring is generally conducted to identify potential sites.

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0167-6105/$ - see front matter
http://dx.doi.org/10.1016/j.jweia.2013.01.007

However, due to financial constraints, this is rarely possible for small urban installations. Bahaj et al. (2007) and Allen et al. (2008) assessed the performance of small wind turbines in urban areas using wind speed data collected at Met Office weather stations however such data are relatively scarce in urban areas. Consequently, to identify the best sites over a wide area there is a reliance on modelled wind speed data. There are several sources of wind resource information available in the UK. In recent years, the DECC wind speed database and Carbon Trust wind speed estimator have been the most commonly used tools. However, recent studies have shown there can be large inaccuracies in their predictions, particularly in urban areas (Encraft, 2009; James et al., 2010).

This paper aims to provide guidance for optimising the placement of small wind turbines in urban areas by developing an improved method of estimating the wind resource across a wide urban area. The first section discusses the tools currently used to estimate the wind resource at a potential site. This is followed by a discussion of the method developed in this study. Finally, the method has been applied to estimate the wind speed across Greater London, from which the best sites for small wind turbines (from an energy production perspective) have been identified.

2. Current methods of estimating the wind resource in urban areas

The DECC wind speed database has been widely used by installers and planners for a number of years to identify sites for the installation of micro-wind turbines (James et al., 2010; Walker, 2011). It provides estimates of the annual mean wind speed at three heights (10, 25 and 45 m) on a 1 km resolution. It was produced by a mass consistent flow model, NOABL (Numerical Objective Analysis of the Boundary Layer), which interpolated wind speed data from 56 weather stations across the UK assuming a uniform surface (Burch and Ravenscroft, 1992). However, studies have shown that the database tends to overestimate the wind speed at urban locations (James et al., 2010). At 16 of the 25 sites considered in the Warwick wind trials the measured wind speed was over 40% lower than the NOABL prediction (Encraft, 2009). The inaccuracy of the database is indicative of the simplicity of the model and in particular the lack of representation of the impact of the underlying urban surface on the flow.

An urban surface affects the flow over a range of horizontal spatial scales: city scale (up to 10 or 20 km), neighbourhood scale (up to 1 or 2 km) and street scale (less than 100 to 200 m) (Britter and Hanna, 2003). At the street scale, interacting wakes are introduced by individual surface obstacles; hence at close proximity to buildings the nature of the flow is dependent on a number of local surface parameters such as building size, shape and orientation. This region of the urban boundary layer is known as the roughness sublayer and extends from the surface up to a height of approximately 2–5 times the mean building height (Roth, 2000).

Blackmore (2008) used wind tunnel experiments to consider flow around a range of different building designs and configurations in the roughness sublayer (i.e. on the street scale). Mertens et al. (2003) and Watson et al. (2007) performed a similar analysis using CFD simulations. The studies showed that at close proximity to buildings the flow is complex; with large variability in the wind speed over small distances. Furthermore, the flow can be characterised by relatively high levels of turbulence, which can have a negative impact on the performance of a small wind turbine (Allen et al., 2008). The results from these studies provide useful guidance as to the best location for small wind turbines above a specific building or within a given street. However due to cost and time constraints, it is not possible to apply this method to consider the wind speed across a wide urban area. Nevertheless, by considering the flow patterns in the roughness sublayer a modified NOABL estimation tool has been developed. The Micro-generation Installation Standard: MIS 3003 applies correction factors to the NOABL wind speed based on turbine height and urbanisation of the site, termed NOABL-MCS (Microgeneration Installation Standard, 2009). While this approach considers the impact of the surface on the flow in the roughness sublayer, it does not consider the impact which occurs on larger scales. Consequently, James et al. (2010) showed that despite the adjustment, the NOABL-MCS still generally overestimates the wind resource in urban areas.

The region directly above the roughness sublayer is known as the inertial sublayer (ISL), which extends up to a height of approximately $0.1z_i$, where z_i is the height of the UBL. In this region the flow around individual buildings is averaged out, therefore the boundary layer has adapted to the integrated effect of the underlying urban surface (city scale). The wind speed in neutral conditions therefore is considered to be horizontally homogeneous and increases logarithmically with height

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z-d}{z_0}\right) \tag{1}$$

where U is the wind speed at a height z, u_* is the friction velocity and k is von Karman's constant. The roughness length, z_0, provides a measure of the drag exerted on the wind by the underlying surface, with a higher value indicating greater drag. When the surface obstacles are densely packed, such as in an urban area, they can be considered collectively as a canopy of mean height, h. This results in a vertical displacement to the wind profile, known as the displacement height, d. While Eq. (1) is strictly only valid in the ISL, Cheng and Castro (2002) and Coceal et al. (2006) have shown that it is also approximately satisfied down to the top of the canopy layer for spatially averaged flow.

The impact of the urban surface on the flow in the ISL forms the basis on the Carbon Trust wind resource assessment tool. The tool enables a user to specify their postcode and the proposed height of the turbine to obtain an estimate of the annual mean wind speed. The model is based on a wind climatology which has uniform validity across the country, derived from the National Climate Information Centre (NCIC) dataset. This is adjusted to the hub height of the turbine assuming a logarithmic wind profile and the presence of a blending height l_b (Best et al., 2008). Below l_b the wind profile is governed by the local surface characteristics, $z_{0\text{local}}$ and d_{local}, while above l_b the wind profile is governed by the effective roughness of a number of surfaces $z_{0\text{eff}}$. Due to the increased consideration of the impact of the surface on the flow, the Carbon Trust tool generally provides more accurate predictions of the wind speed in urban areas than NOABL. However, a field trial carried out by the Energy Saving Trust showed that the tool tends to underestimate the wind resource with an error of up to 20% of the measured wind speed at some sites (Energy Saving Trust, 2009).

2.1. Internal boundary layer approach

When flow encounters a change in surface roughness, such as a boundary between a rural and an urban area, it has to adjust to the new surface characteristics. Elliott (1958) and Panofsky and Dutton (1984) showed that the impact of the new surface gradually propagates upwards and a new boundary layer begins to grow, called an Internal Boundary Layer (IBL). Within the IBL, the wind profile is governed by the local surface characteristics, whereas above the height of the IBL, the wind profile remains characteristic of the upwind surface.