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Assessing the potential of urban wind energy in a major UK city using an analytical model

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An analytical methodology for predicting above-roof mean wind speeds in urban areas is first used to map wind speeds over four different UK cities. The methodology utilises detailed geometric data describing buildings and vegetation to calculate the aerodynamic characteristics of the urban surfaces, and accounts for the influence of building height heterogeneity and wind direction upon wind profiles. The initial objective of the work is to determine the accuracy of the methodology when using detailed geometric data describing building roof shapes in addition to their heights, to estimate surface aerodynamic parameters. By integrating detailed LiDAR (light detection and ranging) data into the methodology and comparing the predictions with measured data, predictive accuracy is found to improve significantly with respect to previous results obtained using less detailed geometric datasets which describe each building with a single height. Subsequently, a preliminary evaluation of the cumulative, city-scale potential for generating wind energy is made, using the UK City of Leeds as a case study. The results suggest that from the point of view of wind resource, 2000 to 9500 viable building-mounted wind turbine locations may exist in Leeds, highlighting the potential for this technology to be far more widely deployed than has presently been achieved. However, the calculations are shown to be highly sensitive to the viable wind speed selected, which in turn depends on financial support and technological progress. An investigation is then made into where, in general, viable roof-top turbine locations may be found. The results suggest that there are viable sites distributed throughout the city, including within the complex city centre, where at the most suitable locations above-roof wind speeds may be comparable to those observed at well exposed rural sites. However, in residential areas, consisting of groups of buildings of similar heights, it is likely that the majority of properties will be unsuitable turbine locations. The wind maps and methodology described in this paper may be utilised by turbine suppliers and customers for assessing the viability of potential sites, as well as being instructive for policymakers developing subsidies for small-scale renewable energy projects.

1. Introduction

If the UK government's legally binding target for CO_2 reduction of 80% by 2050 (compared to a 1990 baseline) is to be reached [1] then every sector of the economy, at every scale, will be required to make the transition to low carbon and energy efficient operations. Energy usage of cities is an important area that must undergo this transition, and distributed, small-scale, renewable energy technologies are expected to contribute to this process.

The installation of small-scale wind turbines on building roofs is one such technology that has received much attention, although not all this attention has been positive. Inadequate assessment of the available wind resource at urban locations, often owing to inappropriate use of the UK's NOABL database to estimate mean wind speeds, has led to some turbines being installed at unsuitable sites resulting in their underperformance [2]. However, as with other forms of wind energy, building-mounted wind turbines can produce significant amounts of electricity and make useful carbon savings when installed at locations with a sufficient wind resource. Therefore, in order for this technology to become more widely deployed, and reach its full potential, it is vital that accurate and affordable methods of estimating wind speeds in urban areas are developed, and that the information is made available to turbine customers.

One method that has shown the potential of accurately estimating wind speeds in urban areas is that recently reported by

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Millward-Hopkins et al. [3]. The method is based upon that originally developed by the UK Meteorological Office [4] (which was reviewed in Ref. [5]) for estimating the wind resource available to small wind turbines. A number of significant modifications were made to the Met Office methodology in order to optimise it for use in urban environments, including the integration of methods to account for the influence of changing wind direction, and the use of detailed data describing buildings and vegetation for quantifying the frictional effect of the urban surface.

By evaluating the model, using measurements from a number of locations, it was concluded in Millward-Hopkins et al. [3] that the predicted wind speeds were reasonably accurate for locations that were exposed to the wind, and hence were considered potentially viable turbine locations. However, when bearing in mind the cubic relationship between wind power and wind speed, the model errors were still significant at a number of sites. As a result of this, it was suggested that the accuracy of the predictions may be improved by using more detailed geometric data when estimating the frictional effect of the urban surface. The aim of this work is to investigate this possibility by incorporating high resolution LiDAR (light detection and ranging) data, which describes buildings and vegetation in great detail, into the methodology developed in Ref. [3].

The outline of the paper is as follows. In Section 2, a description is given of the wind atlas methodology from Ref. [3], the sourcing and processing of the LiDAR input data, and the measurement sites used for evaluating the wind speed predictions. In Section 3.1, results are presented comparing the accuracy of the methodology when using either the LiDAR geometric data or the simpler geometric data used in Ref. [3]. In Sections 3.2 and 3.3, the wind speed predictions are used in conjunction with the geometric data to make a preliminary investigation into the cumulative potential of urban wind energy generation in the city of Leeds, and the influence of the geometric input data on the results is considered. Finally, in Section 4, conclusions of the work are made.

2. Methods

2.1. The wind atlas methodology

The 'wind atlas methodology' [6] used in this paper to estimate mean wind speeds is illustrated in Fig. 1. It involves applying a number of adaptations to a large scale wind speed database to account for the effects of the urban area upon wind profiles. Consequently, it relies upon knowledge of the regional wind climate in the city of interest and also the aerodynamic properties of the urban surface, which are typically quantified using the parameters of roughness length (z_0) and displacement height (d). These aerodynamic parameters control the shape of the standard logarithmic wind profile that is central to the wind atlas methodology:

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

where u_* is the friction velocity, κ is the Von Karman constant (≈ 0.4), and z is the height above the ground. The particular wind atlas methodology we use in this paper is the most detailed of the three described in Ref. [3], which we continue to refer to in this work as 'model MH'. A brief overview of this model is now given.

The regional wind climate used as the starting point of the model in the previous work [3] was the freely available NOABL database [7], however, for the model validation in this paper we use the more sophisticated NCIC database [4]. This contains wind speeds covering the whole of the UK, at a resolution of 1 km, which are valid at a height of 10 m above smooth surfaces equivalent to short grass. Therefore, although these wind speeds account for the influence of the local topography (on length-scales > 1 km), they must be corrected to account for the roughness of the surrounding area before they may describe real, onsite wind speeds. The wind atlas methodology achieves this correction via three scaling procedures.

In the first scaling procedure, the wind speeds from the NCIC database (U_N) are scaled up to the top of the urban boundary layer (UBL), at height z_{UBL}. Here the influence of the urban surface is assumed to be negligible. The logarithmic profile with a reference 'open country' roughness length of 0.14 m (z_{0-ref}) is used for this up-scaling [4], and hence the wind speed at z_{UBL} is given by:

$$U_{UBL} = U_N \frac{\ln(z_{UBL}/z_{0-ref})}{\ln(10/z_{0-ref})}. \tag{2}$$

Due to the fact that the UBL depth increases with increasing distance into the city, the height z_{UBL} is estimated as a function of the distance from the upwind edge of the city [3].

In the remainder of the methodology, the wind speed at the top of the UBL is down-scaled to the turbine hub height in two stages, using aerodynamic parameters appropriate for the urban area. These parameters are estimated based upon detailed

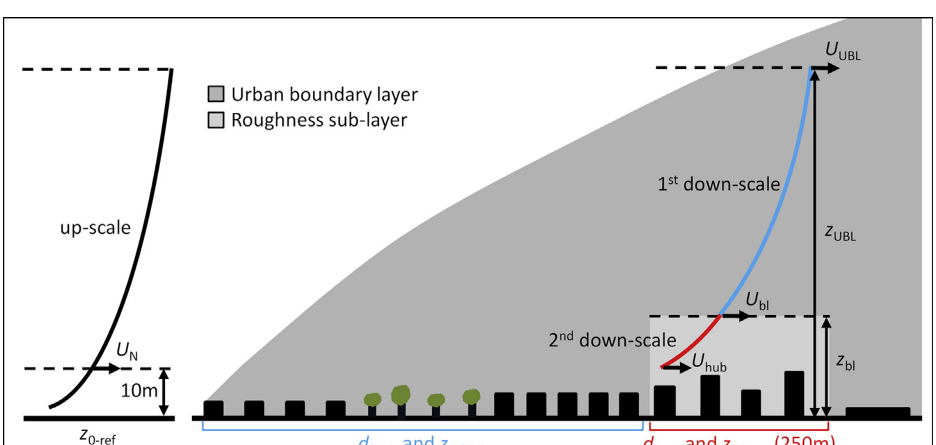

Fig. 1. Schematic diagram of the wind atlas methodology implemented in this work.