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Assessing the Potential of Urban Wind Energy in a Major UK City using an Analytical Model

J. T. Millward-Hopkins, A. S. Tomlin*, L. Ma, D. B. Ingham, M. Pourkashanian.

School of Process, Environmental and Materials Engineering, University of Leeds, Leeds, LS2 9JT.

*A.S.Tomlin@leeds.ac.uk

Abstract

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.

Keywords Building mounted wind turbine, Micro-generation, Wind resource assessment, Small-scale-wind, Urban wind energy, LiDAR data.

1 Introduction

If the UK governments 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 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 [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 & 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:

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

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 [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 1km, 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 > 1km), 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 0.14m ($z_{0\text{-}ref}$) is used for this up-scaling [4], and hence the wind speed at z_{UBL} is given by:

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

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 data describing the geometry of all buildings and major vegetation in the city. The data is discussed further in the following section.

The first down-scaling step is used to estimate the wind speed (U_{bl}) at the blending height (z_{bl}), as illustrated in Fig. 1. The significance of z_{bl} is that it is considered to be the top of the 'roughness sublayer', below which the wind profile is considered to be determined by the local geometry. In our previous work [3], z_{bl} was set to twice the local mean building height (h_{m}) so as to be consistent with the original methodology of the UK Met Office [4]. However, experimental results suggest that this may not be the optimum value [8-11]. Therefore, for the current work a more appropriate value is chosen, and this is described in Section 2.3. The wind profile above z_{bl} is assumed to be influenced by the area directly upwind of the prediction location, extending to a distance of 5 km (referred to as the 'upwind fetch'). The dimensions of this fetch are described precisely in [3]. Consequently, to obtain U_{bl}, aerodynamic parameters appropriate for this fetch are used ($z_{0\text{-fetch}}$ and d_{fetch}) in the logarithmic profile:

$$U_{bl} = U_{UBL} \frac{\ln\left[\left(z_{bl} - d_{fetch}\right)/z_{0-fetch}\right]}{\ln\left[\left(z_{UBL} - d_{fetch}\right)/z_{0-fetch}\right]}. \tag{3}$$

In the second down-scaling step the wind speed (U_{hub}) at the turbine hub height (z_{hub}) is estimated. An assumption is now made that the wind profile is adapted to the local area, and hence aerodynamic parameters estimated for the local, 250m square area ($z_{0\text{-local}}$ and d_{local}) are used to estimate U_{hub}:

$$U_{hub} = U_{bl} \frac{\ln\left[\left(z_{hub} - d_{local}\right)/z_{0-local}\right]}{\ln\left[\left(z_{bl} - d_{local}\right)/z_{0-local}\right]}. \tag{4}$$

For each city, these calculations are carried out for each cell of a square grid on a 250m resolution, and for eight compass wind directions. Subsequently, in order to obtain long term average wind speeds which are independent of wind direction, the predictions for each direction are appropriately weighted by considering the frequency distribution of the wind direction recorded at a local, long-term reference site. The end results of this process are city wide maps of predicted wind speeds for each 250m neighbourhood region at a given height. An example of such a map is shown in Fig. 2 for the City of Edinburgh, where mean wind speeds are calculated at a height of twice the mean building height in each 250 m grid square.

2.2 Geometric Input Data

2.2.1 The Original Datasets

For both down-scaling stages that are illustrated in Fig. 1, the aerodynamic parameters of each city are estimated via the use of 'digital elevation models' (DEMs). These DEMs contain detailed data describing the surface geometry of each city, indicating the above-ground heights of all the surface elements (buildings and vegetation). They are stored in 'raster' format, which are pixelated images of the urban areas, as viewed from above, where the value of each pixel refers to the above-ground height of the surface element at that location. Following the process in Ref. [12] (as discussed in [3]) a number of important geometric parameters can be derived from the DEMs. Subsequently, these geometric parameters can be input into a morphological model [13] to map roughness lengths and displacement heights over each city.

The DEMs used in [3] and [12] were derived from the 'building-heights' data collection that is available from Landmap (http://www.landmap.ac.uk/) through the 'Cities Revealed' agreement (Cities Revealed © The GeoInformation Group 2008). Initially, the data are provided in 'shape-file' format, which stores the footprints of each surface element as vectors with a separate table indicating their maximum above-ground heights. Therefore, before the process in Ref. [12] can be used to estimate aerodynamic parameters, the shape-file data must be converted into raster format. This is easily achieved using the ArcGIS© software.

Although these DEMs contain a high level of geometric detail, assigning each surface element with its maximum height can become problematic when estimating aerodynamic parameters, since average building heights and other similar measures can be overestimated. Consequently, it was suggested in [3] that the predictive accuracy of model MH may be improved if aerodynamic parameters were estimated more accurately. This can be achieved with the use of DEMs which describe the shapes and heights of the surface elements in greater detail. The data we use in the current work to investigate this possibility is now described.

2.2.2 Producing More Detailed Datasets

To consider the cities' geometry in greater detail, we use DEMs based upon LiDAR data. These are measured by a survey aircraft using remote sensing equipment, and are also available from Landmap, who provide them in raster format with a 2 m horizontal and 0.1 m vertical resolution. The remote sensing equipment that is used accurately detects the elevation of any obstructions above the ground. However, different types of surface elements (e.g. buildings, bridges, trees, etc.) are not distinguishable, and furthermore, erroneous heights can occasionally be registered (e.g. rooftop aerials or birds). Therefore, before these DEMs can be used to derive estimates of aerodynamic parameters it is necessary for them to undergo some processing.

The first stage of processing involves removing from the DEM any surface elements which either do not affect the aerodynamic parameters of urban areas significantly, or which may reduce the accuracy of the parameter estimations. This is done with the use of Ordinance Survey MasterMap© data [14] (supplied in shape-file format), which describes the footprints of all fixed ground features greater than a few meters in length or width, such as buildings, roads, woodlands, water features, etc. For each city, the footprints of all buildings and woodland areas are extracted from the MasterMap data, as it is primarily these surface elements that determine aerodynamic parameters. Subsequently, these footprints are overlaid onto the LiDAR DEMs, and everything outside the footprints is set to zero. In addition, any height values that refer to woodlands are reduced in magnitude by 20%, as the porosity of trees means they affect aerodynamic parameters less strongly than buildings of the same height [15]. It should be noted that the most appropriate factor to account for the porosity of vegetation will in practice depend upon both the season and the particular species of tree [15]. However, an average value of 20% is chosen in this work in order to simplify the methodology. Possible variability in this value in reality is not expected to significantly affect the results, as the majority of the surface drag in the cities is due to the buildings.

In the second, final stage of processing, the DEMs are passed through a simple image processing filter in order to remove erroneous height measurements as well as any minor gaps (less than ≈ 2m) in between buildings or within tree canopies. The filter is designed to be minimally invasive: in others words it only filters values in the DEMs which appear to be an unrealistic height relative to the surrounding pixels. Without this filtering, these features can lead to overestimates of the blockage on the flow induced by the surface elements, and hence roughness lengths can be overestimated.

A sample of a resulting set of LiDAR based DEM data is shown in Fig. 3, alongside the equivalent building-heights data which was used in [3]. It can be seen from this figure that the LiDAR data describes building roofs at a higher level of complexity than the building-heights data. Moreover, for the turbine sites used for validation in this work (see Section 2.4), it was found that the heights given by the LiDAR data were far closer to the real, measured building heights than those given by the building-heights dataset. Furthermore, small clusters of trees which are absent in the building-heights data are well captured in the LiDAR data. This enhanced level of geometric detail indicates that aerodynamic parameters may be estimated more accurately from the LiDAR based DEMs.

2.3 The Blending Height

The wind atlas methodology used in [3] remains unchanged in the current work, with the exception of the geometric data described in the previous section, the regional wind climate (now the NCIC database) and also the value used for the blending height. As mentioned in Section 2.1, the blending height was set to $2h_m$ in Ref. [3]. However, experimental results [9-10] show that the urban roughness sublayer is thicker above arrays of buildings of heterogeneous heights, and that it generally extends to 2 - $5h_m$ above the ground depending upon the surface geometry [11].

The implication of this is that a multiple of the ‘effective mean building height’ ($h_{m\text{-eff}}$) may be a more appropriate for estimating z_{bl}, as a characteristic of $h_{m\text{-eff}}$ is that it increases with increasing building height variation [9]. Physically, $h_{m\text{-eff}}$ indicates the effective mean height of an array of buildings that accounts for the disproportionate effect of tall buildings and the negligible effect of small, sheltered buildings upon wind flow. It is predicted by the same methodology used to estimate aerodynamic parameters, z_0 and d, from the DEMs, as described in [3]. Given that, in general, for the four study cities in this work $h_m < h_{m\text{-eff}} < 2.5h_m$, it is appropriate to set $z_{bl} = 2h_{m\text{-eff}}$, as this makes the depth of the roughness sub-layer consistent with the accepted range of 2 - $5h_m$ noted above. Therefore, in the current work a blending height of $2h_{m\text{-eff}}$ is used when using both the Landmap building-heights data and the LiDAR data as input.

Although not shown, an important point to make is that, when using LiDAR data, setting $z_{bl} = 2h_{m\text{-eff}}$ led to a significant increase in overall predictive accuracy relative to predictions made using $z_{bl} = 2h_m$ (with respect to the measured data we consider in Section 3.1). In contrast, when using the Landmap building-heights data, the predictive accuracy of model MH was unchanged whether $z_{bl} = 2h_{m\text{-eff}}$ or $z_{bl} = 2h_m$ was used. It should be noted however, that predictions for individual sites can demonstrate a relatively high sensitivity to the blending height, irrespective of the geometric data used.

2.4 Validation Data

To evaluate the accuracy of the predictions, we use measured mean wind speed data from four large UK cities, namely Edinburgh, Leeds, Manchester and Nottingham. Measurements from 12 anemometers spread over the four cities were available for the model evaluation. The sites range from two-story suburban properties to tall city-centre buildings and the wind speeds are representative of the five year period from 01/08/06 - 01/08/11. In [3], measurements from the City of Warwick were also used in the validation, however, unfortunately LiDAR data was not available for this area and hence these sites had to be discounted from the current work.

By considering the geometric characteristics of the validation sites, each was characterised as *'sheltered'* or '*exposed*'. The former sites are those lying either below the local mean building height or less than 2m above the building roof. All other sites are classed as '*exposed*'. This distinction is made as wind speeds at sheltered sites are difficult to predict accurately without site specific fluid dynamical modelling, but they are also very unlikely to be viable turbine locations.

3 Results and Discussion

3.1 Evaluating the Accuracy of the Predictions

To evaluate the accuracy of the predictions, Fig. 4 (left) shows the predicted (U_{pre}) vs. measured (U_{mes}) wind speeds at each validation site. Predictions at the exposed sites and the sheltered sites are distinguishable in the figure.

It can be observed from these plots that at many of the sites there is an improvement in predictive accuracy when the LiDAR data is used rather than the building-heights data. Moreover, because the rest of the input data remains unchanged for all the predictions in the figure (e.g. the NCIC database and a blending height of $2h_{m\text{-}eff}$), it can be concluded that the use of the LiDAR data is solely responsible for these changes. Considering the predictions site-by-site, the use of LiDAR data appears to either improve the predicted wind speed or have little impact on its accuracy.

The improved predictive accuracy of the LiDAR based predictions relative to the building-heights based predictions is confirmed by considering the box plots of residual errors (defined as U_{mes} - U_{pre}), which are shown in Fig. 4 (right). Although the maximum and minimum residuals are significant, irrespective of which geometric data is used, the median is brought much closer to zero when using the LiDAR data. In addition, the inter-quartile range of the residuals is much narrower when using the LiDAR data. This improvement in accuracy is also evident in the mean absolute error (MAE; ms^{-1}) calculated for the sites:

$$\mathrm{MAE} = \frac{1}{\mathrm{n}}\sum\left|U_{pre} - U_{5yr}\right|. \quad (5)$$

When this error metric is calculated over all the sites, for the predictions based upon the building-heights data is it 0.7 ms^{-1} while for the LiDAR based predictions it is 0.41 ms^{-1}. However, these values are amplified by the sheltered site with the largest error. Consequently, when calculated over just the exposed sites, the MAE is 0.67 ms^{-1} for the building-heights based predictions, and significantly lower at 0.3 ms^{-1} for LiDAR data based predictions.

Some important conclusions can be drawn from considering the bias in the predictions. When using the LiDAR data, the predictions are slightly biased towards over-predictions, whereas with the building-heights data there is a large bias towards under-predictions (see Fig. 4; right). However, the latter under-predictions were not evident in the previous modelling work. This can be explained as a cancellation of the errors inherent in the input data; namely the building-heights data itself and the NOABL wind speeds used to obtain the previous results [3]. Specifically, the NOABL database is known to overestimate wind speeds in built areas [4], while in contrast overestimations of surface aerodynamic parameters (and hence underestimates of predicted wind speeds) have been suggested to arise from the use of the building-heights data [3]. Consequently, as the NCIC database is used as input data in the current work, this error cancellation no longer occurs.

The reasons for the tendency towards over-predictions when using the LiDAR data are not so clear. Potentially, this is due to the fact that, in practice, even those sites classified here as 'exposed' may suffer from sheltering effects due to roof-top flow patterns, and these effects are not accounted for in the current spatially-averaged modelling approach [3]. However, there are also uncertainties in the estimations of the spatially-averaged wind profiles themselves, which can occur even when using fully accurate geometric information [13].

3.2 Evaluating the Cumulative Potential for Urban Wind Energy across Leeds

3.2.1 The Scope of the Investigation

In this section we make a preliminary evaluation of the cumulative, city-scale potential for generating wind energy in urban areas, using the UK City of Leeds as a case study. The assessment involves estimating the total number of suitable roof-top turbine locations that exist in the city based upon the available wind resource (i.e. limitations due to structural and planning constraints are not considered).

McIntyre et al. [16] also assessed the cumulative potential for wind energy generation in the City of Guelph in Canada. The approach used in their work was considerably less detailed than the current work with respect to the modelling of wind flow and identifying suitable turbine locations based upon building data. However, they went on to estimate the cumulative energy generating potential of the turbine installations and made comparisons with the City of Guelph energy usage, and hence the scope of their investigation was much broader in this respect. In future work we intend to make similar energy yield calculations for the City of Leeds.

3.2.2 Approach and Assumptions

We use two different approaches to estimate the number of viable roof-top locations that may exist in Leeds, each of which involves making several assumptions. Note that during this assessment, when using geometric datasets to indentify potential roof-top turbine locations, care must be taken not to include vegetation or other inappropriate data entries. To ensure that these errors are not made, Ordinance Survey MasterMap© data [14] can be used to distinguish buildings from other features within the geometric data set. A further important point to make is that the NCIC database was not avaliable over the whole of Leeds for the current study. At the validation sites for which it was avaliable, the wind speeds were 6 - 9% lower than those in the NOABL database. Therefore, for the assessment in this section the NOABL database is used as a model input, but with the wind speeds reduced uniformly over the city by 7.5%. The map published by the Met Office indicating the differences between the NCIC and NOABL databases suggests this is a reasonable assumption [17].

In the first method (referred to simply as 'method 1'), cumulative roof area is the measure used for the assessment, rather than considering buildings on an individual basis. Calculations are carried out in Matlab©, using a 3-dimensional matrix of predicted mean wind speeds covering the full area of Leeds and extending from ground level up to the height of the tallest building, in conjunction with DEMs of either the building-heights or LiDAR data. Simple calculations, assuming a fixed mast height, lead to an estimate of the total roof area in the city which receives a particular wind speed. By carrying out this calculation over a range of predicted wind speeds Fig. 5 (left) is obtained (assuming here a mast height of 3 m).

The second method (method 2) considers buildings on an individual basis, and begins by making the assumption that one turbine is installed upon the highest part of each building's roof. Subsequently, the number of turbines that may access a particular wind speed is calculated, as shown in Fig. 5 (right). Although this is an intrinsically simple approach, it is not possible to perform the calculations using the raster format DEMs, as these do not distinguish between different buildings. Therefore, the original shape-file format of the Landmap building heights data and the Mastermap data must be used (in the latter case, the height of each building is obtained from the LiDAR DEM), as in this format separate buildings can easily be identified. The shape-file format makes it convenient to carry out these calculations using ArcGIS© software. An advantage of method 2 over method 1 is that it allows different mast heights to be assumed for different size buildings, as the roof area of each building is easily calculated in ArcGIS©. Therefore, for buildings that are most probably residential properties (horizontal roof area < 150m^2) we assume a 2m mast height, while for larger buildings we assume a 5m mast height. It should be noted here that a 2 m mast height is generally not large enough for turbines to escape roof-top flow patterns, and these may be detrimental to their performance. However this mast height is typical of current installations [18].

In order to directly compare the results of methods 1 and 2, for method 1 we make an additional assumption that one turbine is installed every 100m^2 of roof area (assumed to be that of a typical, two-story UK house [19]). Thus, the number of possible turbine locations accessing a particular minimum mean wind speed can be obtained (see Fig. 6, left). The calculations for method 2 from Fig. 5 (right) can easily be translated so as to also describe the number of turbine locations (and therefore individual roofs) accessing a particular minimum mean wind speed (again see Fig. 6, left).

3.2.3 How Many Viable Wind Turbine Locations Exist in Leeds?

Fig. 6 (left) indicates that the four calculations (two different methods and sets of input geometric data) give reasonably consistent results. The different estimates for the number of turbine locations with access to a particular minimum mean wind speed are each within the same order of magnitude. Considering the differences in the four approaches, this is as close an agreement as could be expected. The range of these estimates provides an indication of the uncertainty within the predictions.

To suggest an estimated value for the number of viable wind turbine locations that may exist in Leeds, it is necessary to make a final assumption regarding the minimum on-site mean wind speed that is required. In reality, this value will depend on many factors such as the particular turbine design (which impacts on its power curve), the long-term wind speed distribution, and financial and environmental considerations such as overall installation costs vs. income generated. Financial incentives such as Feed in Tariff framework present in the UK [20] can have a particularly significant influence upon the wind resource required for financial payback to be achieved.

In order to make an appropriate estimate of this minimum wind speed required, we consider energy production data obtained from the Warwick Wind Trials [18] (for currently available small-scale, horizontal-axis wind turbines). Four different types of site are chosen ranging from rural to high rise urban locations, and the measured monthly capacity factors for the turbines at these sites are shown in Fig. 7. The figure indicates that when mean wind speeds are less than 4 ms^{-1}, turbine performance is generally quite poor and difficult to predict, although for wind speeds just over 3.5 ms^{-1} capacity factors of around 6% appear to be attainable, and this may be sufficient performance for financial payback to be achieved in the UK [20] (although this depends upon a number of economic factors). At higher wind speeds the measured capacity factors start to become much better correlated with wind speed, and at about 4.5 ms^{-1} capacity factors reach the commonly quoted manufacturer's value of 10% [21] (for building mounted installations).

For these reasons, we choose a minimum viable wind speed of 4ms^{-1} for this assessment, but we test the sensitivity to this choice by also considering wind speeds of 3 ms^{-1} and of 5 ms^{-1}. Respectively, these alternative wind speeds could be considered to represent scenarios where more advanced low wind speed turbines become available, or there are significant reductions in financial subsidies.

The results in Fig. 6 (right) indicate that the number of viable turbine locations in Leeds is estimated to be within the region of 2000 to 9500 assuming a minimum viable wind speed of 4 ms^{-1}. The variation in these estimations is due to differences in the method and geometric data used, but the values appear to be more sensitive to the minimum wind speed chosen. Specifically, when a value of 3 ms^{-1} (or 5 ms^{-1}) is chosen, then the estimates increase (or decrease) by a factor of ≈ 7 (or ≈ 10), to between 11000 and 64000 (or 200 and 1000) viable turbine sites. It is worth mentioning that even if wind turbines were installed in Leeds at the highest density suggested by this viability study, we do not expect them to have a significant effect upon the wind resource available in the city.

In summary, considering that there are currently only a handful of roof-top turbines installed within Leeds [22-23], these results highlight the potential for small scale wind technology to be far more widely deployed than has currently been achieved, provided care is taken when assessing site suitability. In addition, they demonstrate the high sensitivity of the technology's potential to the minimum wind resource required to make an installation viable, which in turn may be strongly influenced by technological progress and levels of financial support.

3.3 Variation in the Available Wind Resource across the City

Finally, it is important to discuss where, in general, viable roof-top turbine locations may be found. Fig. 8 (top) shows the long-term predicted mean wind speeds over Leeds (LiDAR based) at 10m above the mean building height in each 250m resolution grid square. It suggests that the wind speeds at this height are highest around the cities edge, and that as the city centre is approached they decrease consistently. This pattern arises as the surface roughness in the city centre is typically much higher —and the urban boundary layer thicker— than in the outskirts of the city. Considering the magnitude of these wind speeds, the installation of turbines at heights (i.e. building plus mast height) that do *not* exceed the local average building height by 10 m should generally only be considered for locations in the outer few kilometres of Leeds. Further into the city centre, the predicted wind speeds at this height are typically below $4ms^{-1}$.

When the predicted wind speeds 3 m above the highest building within each grid square are considered (Fig. 8, bottom), a different pattern emerges to that found in Fig. 8 (top). It is clear from this figure that throughout much of the city there are tall buildings with access to significant mean wind speeds (frequently over $5ms^{-1}$.) Furthermore, as well as on the outer edges of Leeds, the highest wind speeds are now found in the city centre where there are many tall, exposed buildings with access to relatively undisturbed winds, despite the high roughness of the surrounding area. This is illustrated more clearly in Fig. 9 (right), which shows the predicted wind speeds above each building roof in an area of the city centre. In actual fact, the potential for wind energy generation above these tall buildings is likely to be significantly greater than is indicated in Figs. 8 & 9 (top & right), as upon larger buildings roofs mast heights as tall as 10 m may be feasible. In contrast to this, buildings within surrounding residential areas are often all of a similar height (e.g. Fig. 9, left), and hence above the majority of these properties, wind speeds may be too low for turbine installation to be worthwhile.

Overall these results indicate that, although there are many buildings for which the installation of a rooftop turbine should not be recommended (particularly residential properties), there are many tall buildings upon which the installation of a rooftop turbine with a reasonably tall mast is likely to be a worthy investment. Furthermore, above the roof of exposed buildings which are significantly taller than those in the local area (such as blocks of flats and high-rise city centre buildings), the wind resource may be very favourable and comparable with well exposed rural sites [5].

4 Conclusions

An analytical methodology for predicting above-roof mean wind speeds in urban areas has been used to map wind speeds over four different UK cities. The methodology, which was previously developed by Millward-Hopkins et al. [3], 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 first objective of the work was to determine whether the predictive accuracy of the methodology could be improved by using more detailed geometric data than that used in Ref. [3] to estimate surface aerodynamic parameters. Accordingly, LiDAR data was used as geometric data for model input, which describes building roof shapes in addition to their heights. When the predictions were evaluated against measured mean wind speeds from 12 anemometers spread over the four cities, the use of LiDAR data was shown to improve model accuracy significantly. At the sites which were well exposed to the wind, the mean absolute error in the predictions was reduced from 0.67 ms^{-1} to 0.3 ms^{-1} when LiDAR data was used, with respect to the predictions made using the building heights data. The results also suggested that the accuracy of the predictions in Ref. [3] had benefited from error cancellation, as uncertainties in the geometric input data had worked in opposition to uncertainties in the regional wind climate (i.e. the NOABL database).

A preliminary evaluation of the cumulative, city-scale potential for generating wind energy was then made, using the UK City of Leeds as a case study. The assessment involved estimating the total number of viable roof-top wind turbine locations in the city, based upon them receiving a sufficiently high mean wind speed. The results depended upon the method and building data used in the calculations, but more strongly upon the required minimum mean wind speed that is assumed. Potentially, this highlights the sensitivity of this technology's potential to financial support and technological progress. When a minimum value of 4 ms^{-1} is assumed, the results suggest 2000 to 9500 viable building-mounted wind turbine locations exist in Leeds, and hence there appears to be huge scope for the technology to be more widely deployed.

Finally, it was investigated where, in general, viable roof-top turbine locations may be found. The results suggested that there are many viable sites (typically tall unsheltered buildings) that are distributed throughout the city, including within the complex city centre. At the most suitable sites predicted above-roof mean wind speeds are comparable to those observed at well exposed rural sites. In residential areas however, which consist of buildings of a similar height, it is likely that the majority of properties will experience wind speeds that are too low for turbine installation to be worthwhile.

The wind maps and methodology developed in this work 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.

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Figures

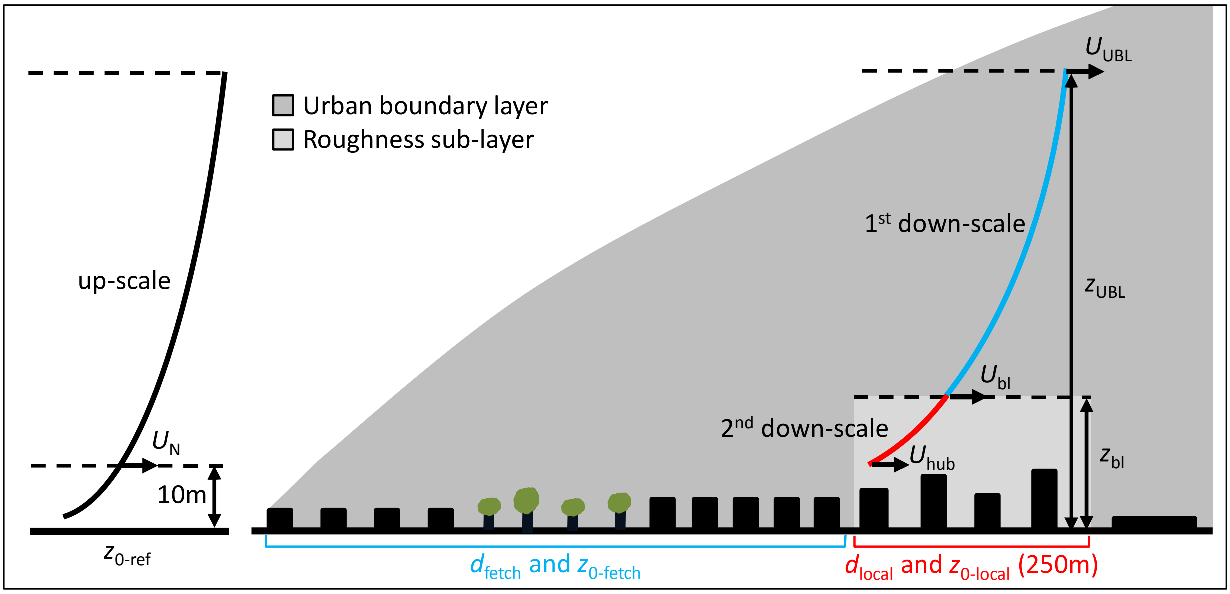

Figure 1: Schematic diagrams of the wind atlas methodology implemented in this work.

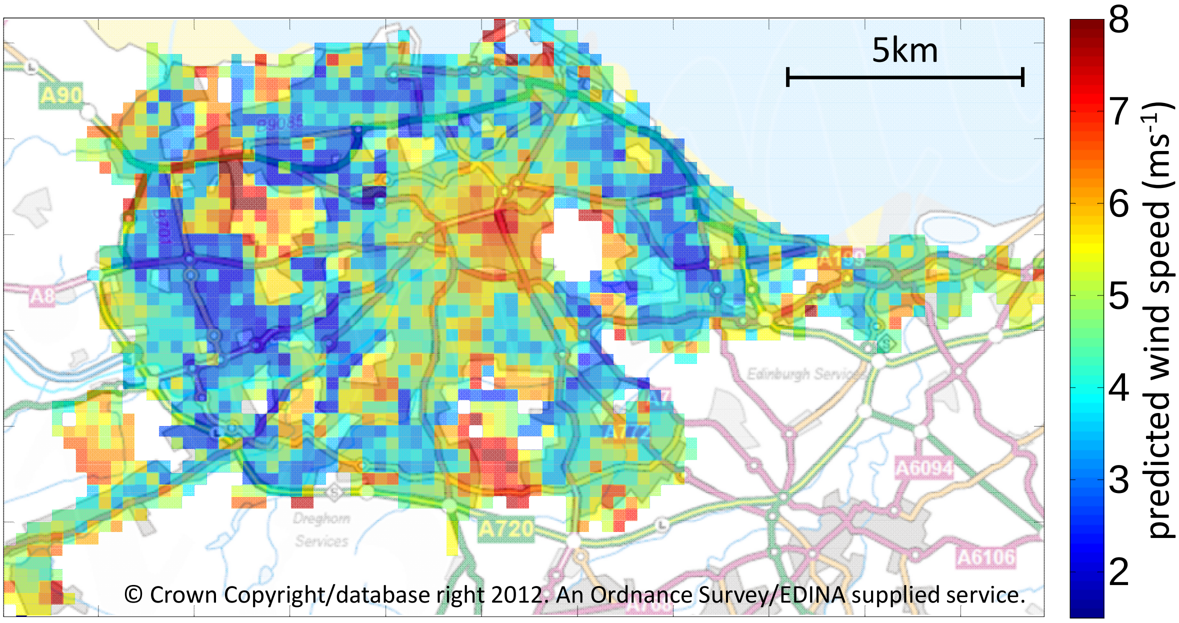

Figure 2: Predicted mean wind speeds mapped over the City of Edinburgh at a resolution of 250 m. The predictions are made using the building heights data as in Ref. [3], at a height of twice the mean building height in each 250 m grid square.

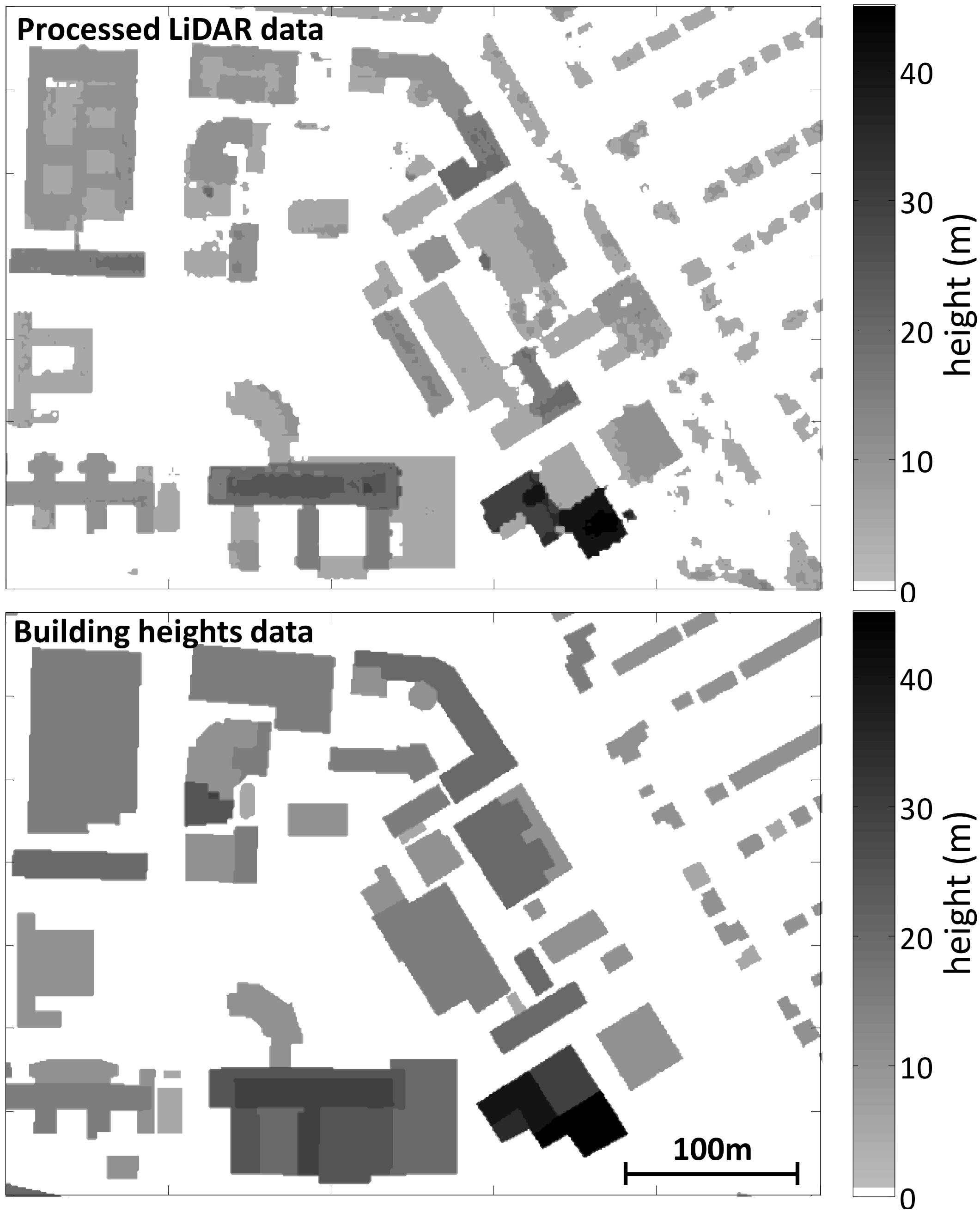

Figure 3: Examples of the two sets of geometric data for a sample area of Edinburgh.

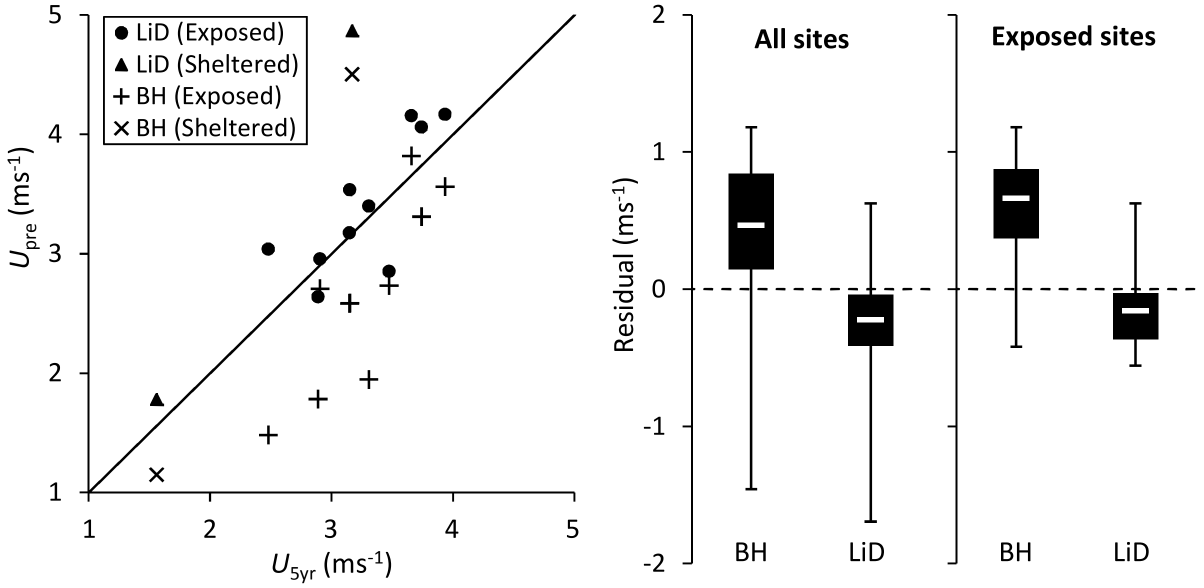

Figure 4: Shown on the left, comparisons of predicted (U_{pre}) and measured, 5 year corrected (U_{5yr}) wind speeds for at the validation locations using both the LiDAR (LiD) and building heights (BH) geometric input data. Shown on the right, box plots of the residual errors (ms^{-1}) indicating their inter-quartile range (black boxes), median (white horizontal dashes) and maximums and minimums (error bars) when using each set of input data.

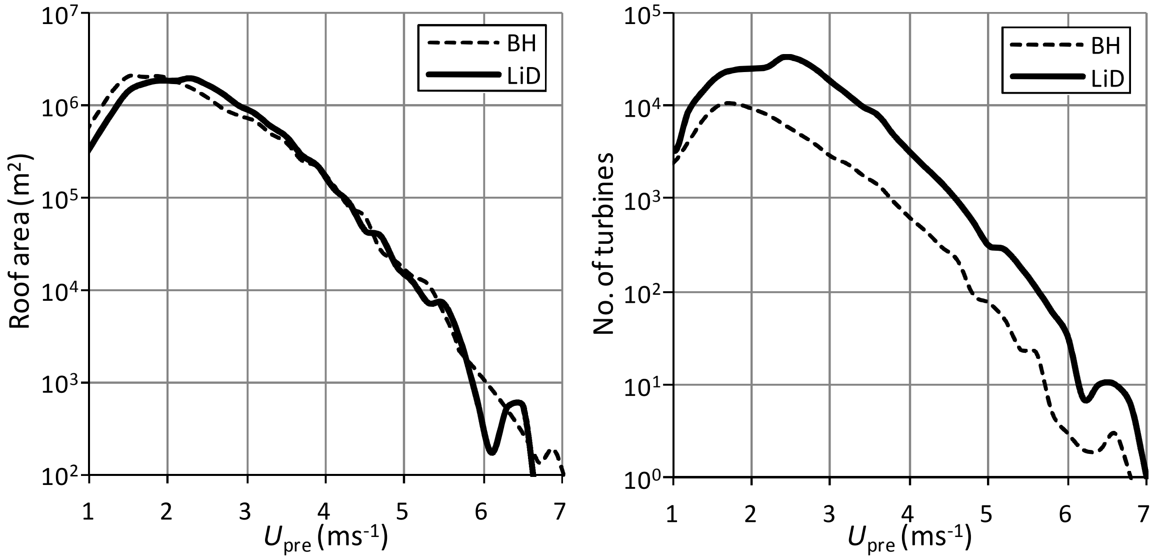

Figure 5: The total roof area in Leeds (left) estimated to receive each of the wind speeds recorded on the x-axis, assuming a 3 m mast height. The number of roof-top turbine locations in Leeds (right) estimated to receive each of the wind speeds recorded on the x-axis, assuming one turbine is installed per building roof with a mast height of 2 m for small buildings (horizontal roof area < 150 m^2) and 5 m for larger buildings.

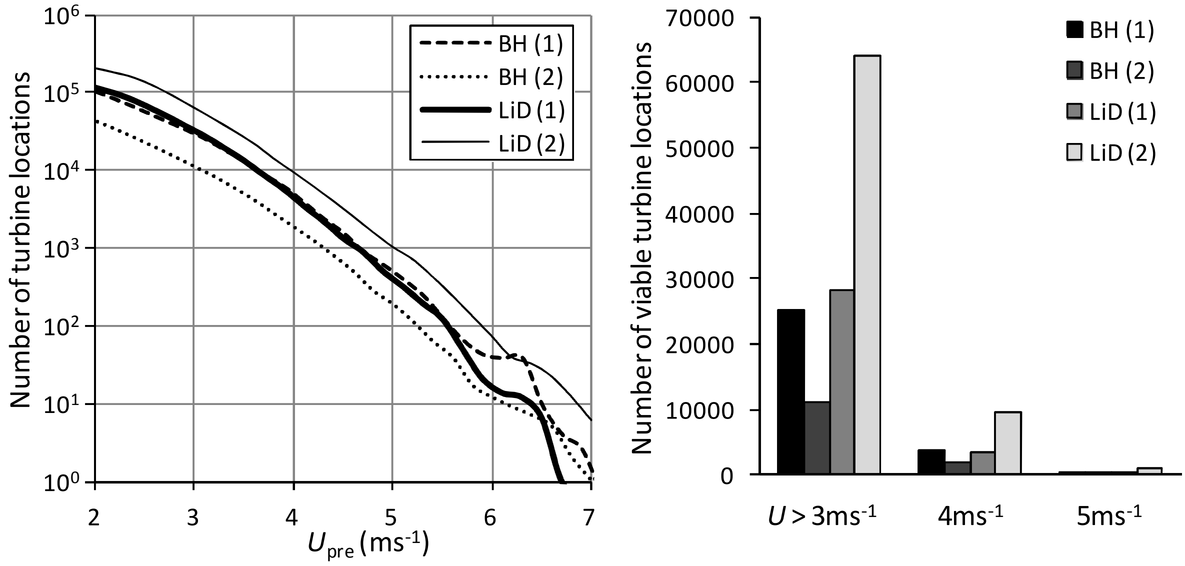

Figure 6: The number of roof-top turbine locations in Leeds estimated to receive the minimum wind speeds recorded on the horizontal axis (left). The number of viable roof-top turbine locations estimated to exist in Leeds (right). The estimates shown are made using methods (1) and (2) in combination with each set of geometric input data.

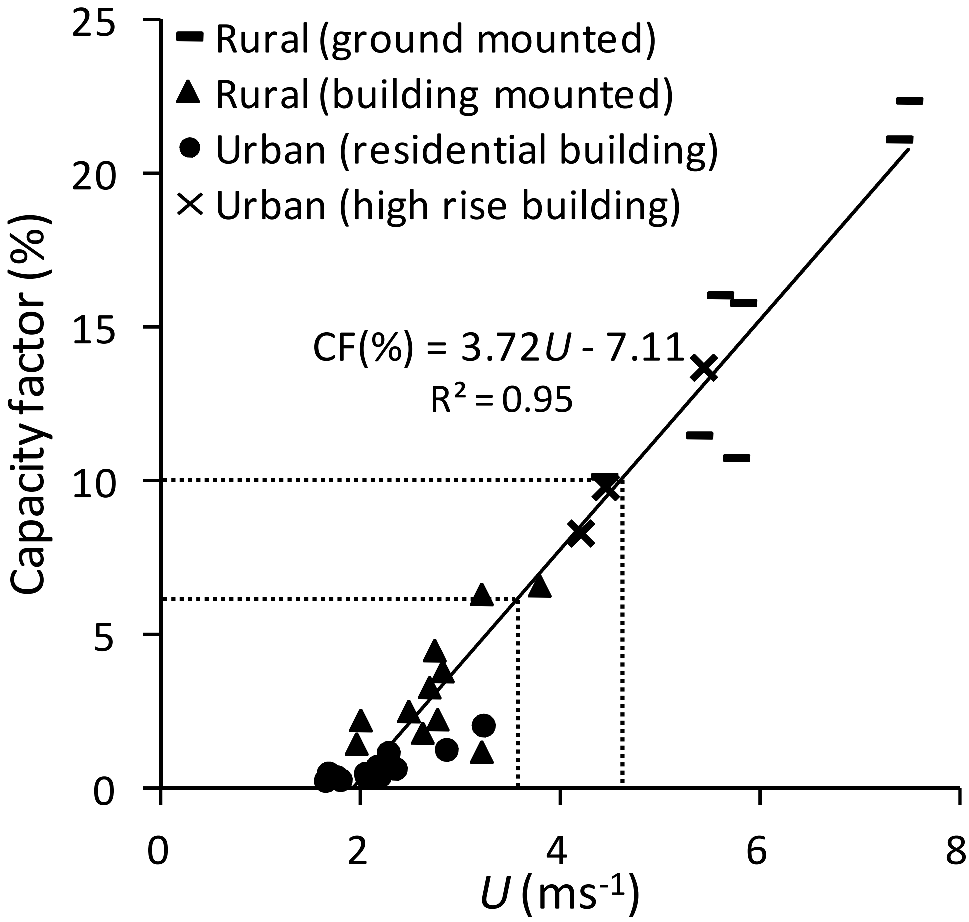

Figure 7: The relationship between turbine capacity factor (measured monthly) and mean wind speed for small-scale, horizontal-axis wind turbines installed at a variety of sites during the Warwick Wind Trials [20].

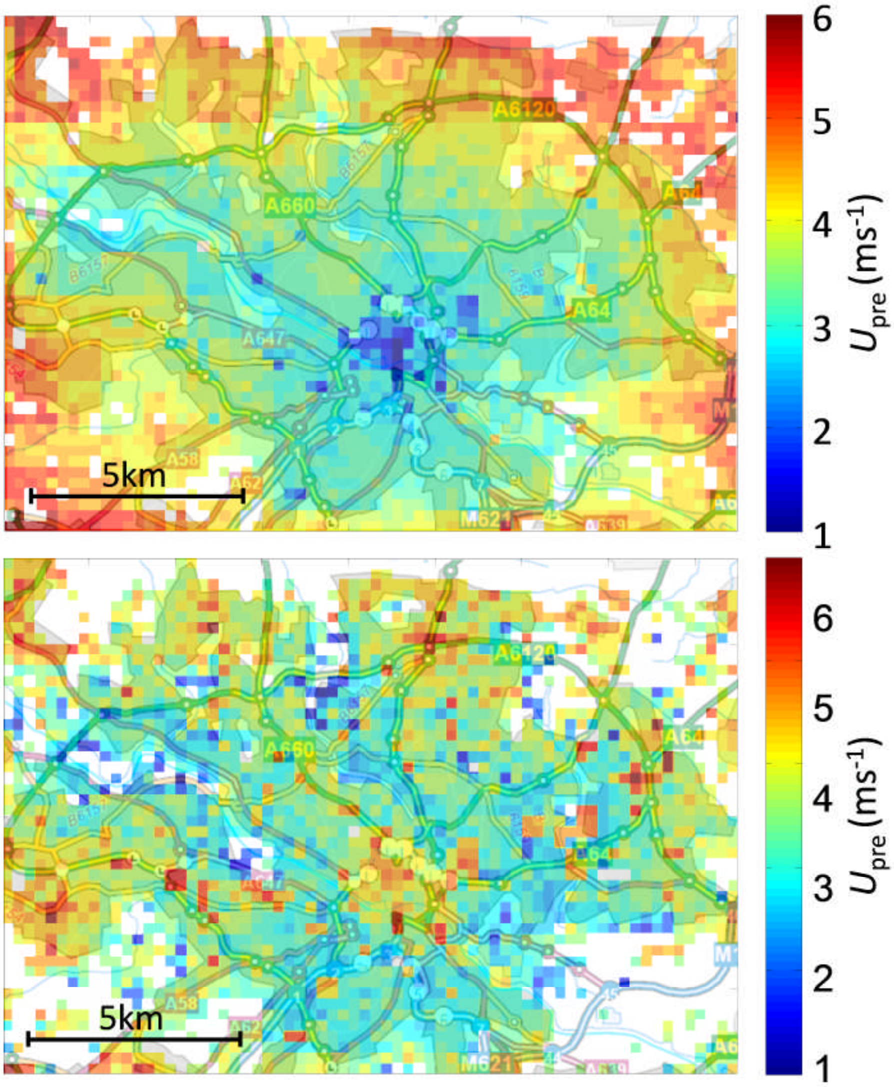

Figure 8: Maps of predicted, long-term mean wind speeds over the Leeds at a resolution of 250 m, made using the LiDAR data. The predictions are made at a height of 10 m above the mean building height in each 250 m grid square (top) and at a 3 m mast height above the maximum building height in each 250 m grid square (bottom).

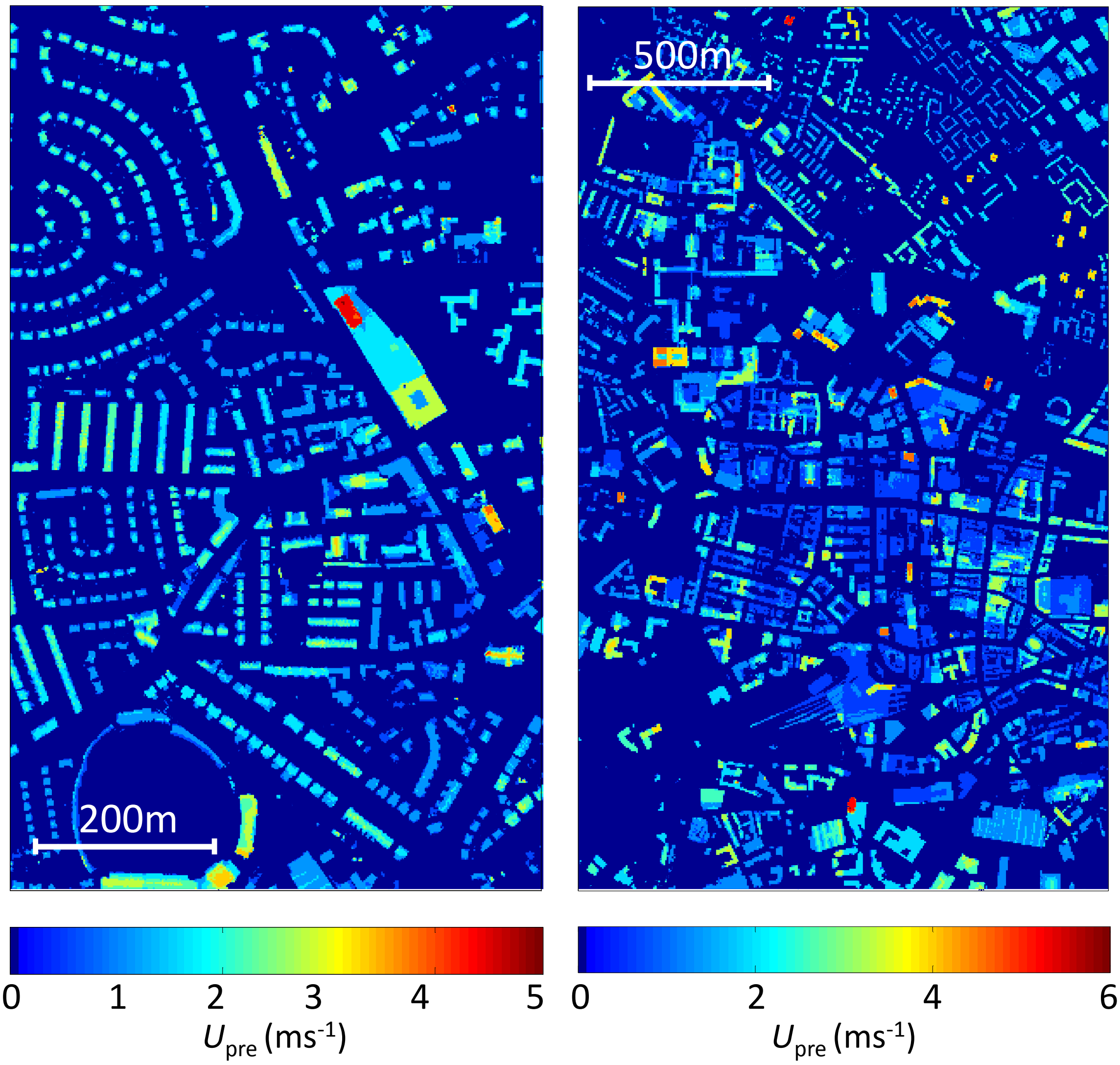

Figure 9: Maps of a sample residential area (left) and the city centre (right) of Leeds, indicating the predicted wind speeds above each building roof. Mast heights of 2 m (left) and 5 m (right) are assumed. Note the colour-bars differ between the two figures.