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Building mounted wind turbines and their suitability for the urban scale—A review of methods of estimating urban wind resource

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ABSTRACT

In this paper, a review is presented of academic literature regarding urban wind speeds for building mounted wind turbines. Site measurement of wind speed requires time and money that often are not available for small micro-generation projects. Research into wind speed estimation for the urban environment has shown that street canyons affect urban wind flow, that wind speed up over the roof ridge is only evident for isolated single buildings, that the wind resource "seen" by a building mounted wind turbine is affected by positioning (height above roof ridge and position relative to the prevailing wind direction), that urban terrain roughness is high, and that adjacent buildings can cause wind shadow. This multiplicity of factors makes it difficult to generalise a wind resource estimation methodology for the urban environment. Scaling factors may prove to be a practical solution, provided the accuracy of their use is well understood.

1. Introduction

The UK government created legislatively binding targets for CO_2 reduction of 80% by 2050 (compared to a 1990 baseline) in 2008 [1]. All economic sectors are expected to contribute to a climate change programme of energy efficiency, switching to lower carbon fuels, increased use of renewable energy and transfer to a hydrogen/zero carbon economy [2,3]. Energy policy is a key delivery mechanism for the climate change programme, and with approximately 50% of UK energy use in buildings [4], the focus has fallen justifiably on the built environment to deliver carbon savings. Within the domestic sector, increased use of renewable energy is achievable through wider adoption of micro-generation. Micro-generation is also subject to a number of legislative drivers in the UK, including the micro-generation strategy [5], the Low Carbon Buildings Programme [6], the Renewables Obligation Order [7], the Code for Sustainable Homes [8], the Energy Performance of Buildings Directive [9,10], the Feed-in Tariffs Order [11] and the Renewable Heat Incentive [12].

Building mounted wind turbines are coming under increasing scrutiny as part of a group of technologies suitable for domestic micro-generation applications. It is therefore timely to consider the suitability of building mounted wind turbines in the urban environment. This paper shall provide a review of the academic literature on the methods for prediction of urban wind speeds and urban wind power production.

2. Urban wind speeds

Urban wind turbines mounted on buildings are within the surface roughness layer, which extends above surface elements to at least 1–3 times their height (see Fig. 1). This layer is significantly influenced by surface features and air flow is highly irregular in this region. Therefore the wind speeds experienced by the wind turbine are significantly affected by the surface features.

Research into boundary layer climates in urban areas has predominantly been driven by an interest in pollution dispersal, and to a lesser extent pedestrian comfort. Very little research has been conducted into urban wind speeds with a view to wind turbine applications.

2.1. Theory

Wind speed within the planetary boundary layer increases logarithmically with height. The neutral wind profile extrapolates to zero wind speed at zero displacement height (d) when measured above vegetation or buildings [13–15], as shown in Eq. (1).

$$\bar{u}(z) = \frac{u_*}{k} Ln\left(\frac{z-d}{z_o}\right) \quad (1)$$

where u_* = friction velocity, k = von Karman's constant, z_o = roughness length, d = displacement height and $\bar{u}(z)$ = average wind speed at height z above ground. This equation is

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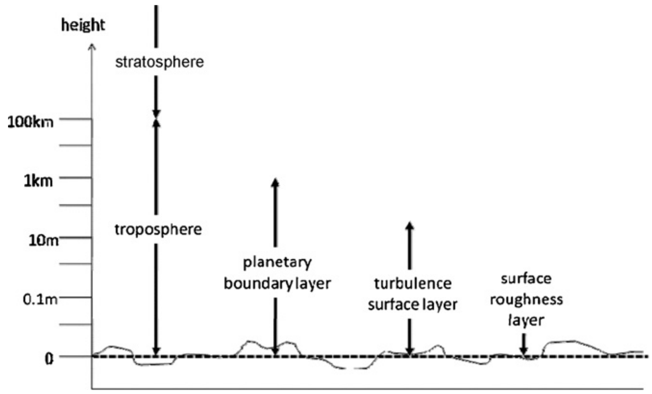

Fig. 1. Vertical layers of the atmosphere.
Adapted from Oke [13].

considered applicable to heights above 2 h from the ground, where h is the height of the roughness obstacle.

Jian-Zhong et al. [15] expanded on this relationship for wind speed within the surface roughness layer, i.e. at heights of less than 2 h, as shown in Eq. (2).

$$U_h = \frac{\alpha u_*}{k} Ln\left(\frac{h-d}{z_o}\right) \tag{2}$$

where α = wake factor and U_h is the wind speed at height h. The authors also derived a relationship for the dimensionless roughness length, Eq. (3).

$$\frac{z_o}{h} = \left(1-\frac{d}{h}\right)\exp\left[-\left(0.5\frac{\alpha^2}{k^2}C_D\lambda_f\right)^{-0.5}\right] \tag{3}$$

where C_D = drag coefficient and λ_f = frontal area density (ratio of total front area of obstacles to total area covered by obstacles).

Heath, Watson and Walshe [14] described the wind speed at heights below obstacle height h as an exponential rather than logarithmic relationship, shown in Eq. (4).

$$U(z) = U_h \exp\left(a\left(\frac{z}{h}-1\right)\right) \tag{4}$$

where a is a constant which is dependent on building morphology, approximately 9.6λ_f for an array of cubes.

Instantaneous power production from wind turbines in the urban environment is dependent upon the kinetic energy in the wind and the efficiency of extraction of that energy by the wind turbine. This is usually described as shown in Eq. (5).

$$P_{turbine}(u) = C_p\frac{\rho A u^3}{2} = C_p\frac{\pi\rho d^2 u^3}{8} \tag{5}$$

where $P_{turbine}(u)$ is the power output of the wind turbine for wind speed u, ρ is the density of air, A is the rotor swept area, d is the rotor diameter and C_p is the power coefficient [16].

Since the power output from a wind turbine is related to the site wind speed by a cubic law, accurate estimation of the site wind speed is vital for accuracy of power output estimates.

2.2. In situ measurement of wind speed

Eliasson et al. [17] conducted measurement of three-dimensional wind velocities for a narrow (height-to-width ratio 2:1) street canyon in Sweden. With ultrasonic anemometers at three positions above the roof in addition to within the canyon, this is one of a handful of in situ measurements with data on above-roof wind speeds, although much of the analysis and discussion referred to in-canyon (i.e. below roofline, between building) conditions. The data used was taken on days of clear sky conditions to limit the number of external weather variables to solar radiation (measured as between 84% and 98% of modelled clear sky conditions) and air temperature. Their findings showed that once adjustment was made for the simultaneous estimation of roughness length and displacement height, the wind speed measurements "closely" matched the expected logarithmic relationship, although no statistics were presented to confirm this finding. Their results did not show an expected strong shear layer at roof level, although graphical data did show that the extent of the shear was dependent on prevailing wind direction. The weakness of the shear at roof level was perhaps due to the positioning of the highest sensor, results from which were used to normalise the data. Vector wind velocities were sampled at 10 Hz and statistics (mean, variance, covariance, skewness and kurtosis) calculated for 5 min intervals. Results were only published for 13 autumn days however, and therefore this small, time bound, sample may not be representative of all categories of conditions within the surface roughness layer (both within and above the canyon). The authors did not include any discussion on the potential for results to be generalised to other times of the year or other locations.

An earlier study by Roth and Oke [18] also measured three-dimensional wind velocities, at two heights above ground in an urban area in Canada. Appropriate instrument calibration was undertaken, and the statistical analysis of data was described in detail. The authors analysed data as spectra, which makes results difficult to compare with other studies. Some data was identified as poor quality for the sensor located closer to the ground. This data was replaced with interpolated data, derived from an assumption that the relationship between wind speed at the two measurement heights was a constant. Results of the velocity spectra (adjusted for displacement height) for the vertical component did not correspond well to a logarithmic profile. It is not clear in the paper whether displacement height varied with wind direction or was assumed to be one representative value. When results were compared with reference data, the authors considered the variations to be of "moderate magnitude", although the irregularities expected due to building wakes were not present in the data and the statistical analysis of variance between reference data and test data was not provided. A relatively small sample of data was used in this research (40 sets of 60-min data collection periods in July), and therefore this data may not be representative of all categories of conditions within the surface roughness layer. The authors considered that results showed a relatively small spatial inhomogeneity of the roughness sub layer, and that therefore results should be applicable to other urban areas. However, no quantitative measure of the spatial inhomogeneity was provided.

The same field data was used by Roth [19] to define the drag coefficient and turbulence intensity of the wind. Turbulence intensity is defined as the ratio of the standard deviation of the respective wind component to the mean wind speed, shown in Eq. (6).

$$I_i = \frac{\sigma_i}{U} \tag{6}$$

where i = u, v, and w the three components of wind speed, U is the mean wind speed and σ_i is the standard deviation of the respective wind component.

2.3. Wind tunnel tests

In situ measurement of wind speed in the urban environment is relatively limited. The papers reviewed here have used a sample of days which may not be representative of all categories of conditions within the surface roughness layer. Eliasson et al. [17] obtained results of wind speed with height which matched the theoretical relationship shown in Eq. (1). Further data for urban wind velocity at and just above roof height, for high sampling frequencies, is vital when considering the suitability of wind turbines for urban applications, since high sampling frequencies will enable appropriate analysis of the effect of turbulence on urban wind speeds.

Rather than take in situ measurements, where extraneous variables are more difficult to control, some research has been undertaken into the effect of buildings on urban wind speed through controlled simulation in wind tunnel experiments.

Rafailidis [20] conducted wind tunnel experiments to measure wind flows around building models. Measurements were taken using laser Doppler anemometry or hot film anemometry (sensor accuracy and placement not detailed) and instantaneous measurements were averaged over four minutes (sampling frequency of instantaneous measurements was not specified). Results were limited to the investigation of one upstream wind speed, two building geometries, and two building densities. Rafailidis showed that wind speeds were mildly retarded above a flat roof, and more significantly retarded above slanted roofs (statistical significance not provided), with the effect of building obstacles on air flow nonexistent at heights of three to five combined building heights above ground. Although Reynolds stress was reduced for higher building densities, results demonstrated significant differences in wind parameters for high building densities compared with a flat plate, and a greater turbulence intensity close to roof tops for pitched roof compared to flat roof geometries.

Kastner-Klein et al. [21] conducted wind tunnel experiments for a single canyon with a height-to-width ratio of 1, for two canyon lengths. Wind speed data was normalised for the vertical component by the value of the mean wind speed at height $z = H$ (H being the canyon height). Immediately above roof level, the results showed a strong mean flow shear, with sharp vertical gradients of the mean velocity. There was a slight increase in root mean square velocity values immediately above roof level, where flow shear led to intensified turbulence. The methodology of measurement and time period of averages were unclear. Transient effects were not considered by the authors, and the paper neglects to specify the controlled approach flow conditions, such as wind speed and surface roughness of the surrounding upstream area.

Blackmore [22,23] investigated wind flow around terraced and detached buildings using wind tunnel tests. In tests the following parameters were controlled: roof pitch (two values based on English Housing Condition Survey data of unspecified age), upwind surface roughness (two values based on a British Standard), hub height (three values measured above roof height), distance to surrounding buildings (three values) and wind direction (four values). The detached and terrace buildings were one size of each type, described as “representative” in size. Horizontal wind speed was measured at three heights using hot wire anemometers, the accuracy of which was specified. Wind speed measurements over a 20 s 100 Hz sample for each measurement location were averaged. Measurements were taken over one quarter of the roof, assuming a wind profile symmetry which was not confirmed through measurement. Computation fluid dynamics (CFD) modelling would not support this assumption of symmetric flows (see, for example, Heath et al. [14]). Without any building obstruction, wind speed measurements agreed well with predicted values based on a logarithmic relationship [Eq. (1)]. Results of wind speed measurements around a building showed wind speed was more directionally dependent for a steeper roof pitch, that a lower surface roughness resulted in lower levels of turbulence, and that surrounding buildings had a greater affect on wind speed around and above roof height when wind direction was perpendicular to the roof ridge. The author makes reference to patterns of wind speed results at 1.5 m, 3 m and 4.5 m above roof height, although the absolute height above ground varies dependent upon whether measurements were taken at a mounting position near the eaves or the ridge. The author used the results to make recommendations as to mounting locations for micro-wind turbines above roof level. The author also recommended that estimates of micro-wind turbine power output be based on wind speed estimates using a Weibull cumulative distribution function (CDF) of the form shown in Eq. (7). No interpolation of results was provided for semi-detached properties, the second most common property type according to data provided from the English Housing Condition Survey.

$$P = 1 - \exp\left(-\left(\frac{V}{c}\right)^{k}\right) \tag{7}$$

where P is the Weibull cumulative distribution function, c is the scale parameter, k the shape parameter and V the wind speed.

The research described above have all used wind tunnel tests to investigate free-flow wind speeds above surface roughness elements. Danneker and Grant [24] used wind tunnel tests to investigate wind speed measurements within ducts. The authors investigated wind speeds in a 30° and 90° duct with and without spoiler. Surface roughness of the ground plane around the building model was not specified, and the dimensions of the building were not clearly defined. Results indicate flow within the duct of 35–40% (for 30° duct) and over 40% (for 90° duct) greater than the upstream wind speed for wind speed incident angles of up to 60° from normal. The authors calculated mean values of parameters based on 4096 samples (1 kHz sampling frequency). No analysis is made of multiple ducts, although the authors hypothesise that installation of several ducts could result in an overall drop in pressure on the leeward side of the building. Only one free flow wind speed of 16.5 $\mathrm{ms^{-1}}$ was investigated and therefore it is difficult to ascertain the relevance of the results for lower wind speed values, where conditions of flow separation and jet entrainment may be very different.

The wind tunnel investigations reviewed here do not investigate a range of upstream wind speeds. None of the research made clear reference to upstream wind speeds and the vertical wind profile. Several experiments found that there is less wind shear at the roof edge for multiple (urban) building configurations when compared with wind shear at the roof edge for a single building. Blackmore [22,23] found that wind speed at different roof locations is dependent on the prevailing wind direction, and Danneker and Grant [24] found wind speed increased within ducts.

2.4. Computational fluid dynamics and mathematical modelling

Unless stated otherwise, the computational fluid dynamics (CFD) studies of wind velocity around obstacles described below have all used Navier–Stokes equations for unsteady incompressible viscous flow. Many of the studies reviewed have considered CFD applications for the study of air movement within urban street canyons, for applications of pollution dispersal, and this area of research is of less relevance to building mounted wind turbines. Very little CFD work has been undertaken expressly to consider air movement at and immediately above roof height, for applications of building mounted wind turbines.

Heath, Watson and Walshe [14] validated CFD results against wind tunnel tests for a cube shaped obstacle, and found their results were in agreement for wind speeds upstream and around the obstacle (no statistical comparison of results is provided but a graphical representation is included). Downstream results showed a degree of error which the authors attributed to the choice of turbulence model (k–ε). A CFD model was then generated for simulated streets of houses in a staggered array, with a clearly defined set of parameters. Results showed there was a slight increase in wind speed as wind is forced between buildings, and wake patterns downwind of building obstacles. These results were based on 0.5 s velocity values averaged over a 10 s period. Velocity across the building array was generally lower than the upstream wind speed. Below roof height, velocity was very low. Closer to roof ridge height, velocity decreased as the wind approached the roof, increased very slightly as the wind crossed the ridge, and then slowed again. There was virtually no speed-up effect across roof ridge in a street array, which is markedly different to CFD results for velocity profiles across an isolated building. An analysis was made in the CFD model of the wind velocity profile at four possible wind turbine mounting locations. For the modelled north-south street alignment, the authors determined a local effect coefficient l (the ratio of the mean wind velocity at mounting height to the mean wind velocity at the mean building height) for four different roof mounting points and three different mounting heights, for eight wind directions. The authors showed height had a large impact on mean wind speed, and regardless of the mounting location the mean wind speed varied considerably with wind direction. They also found that different mounting positions were better suited to different prevailing wind situations, but that the centre of the roof was consistently the poorest performing position. Despite the identified inaccuracies of downwind results when modelling a simple cube, the authors made no correction to the k–ε model when considering the wind profile around buildings in the fourth row downwind of the urban "edge".

A cursory comparison between the local effect coefficient in Heath, Watson and Walsh [14] and roof positional scaling factors in Blackmore [23] for wind speeds 3 m above building height, for a roof pitch 45–50°, show good agreement (within 5%) for the wind direction range 90–180°.

Lu and Ip [25] used CFD analysis to consider high rise applications of wind turbines in Hong Kong. The inlet wind profile is defined, as is the building geometry considered. However, boundary conditions and surface roughness are not defined, nor is the turbulence in free flow conditions. Investigating building separation, building height and building roof shape on wind velocity between and above tall buildings, CFD results showed a concentration effect between the buildings with wind speed increased compared with free flow, although the extent of the increase was similar for the two building heights investigated. Simulations showed a turbulence layer which was thicker at the roof centre and thinner at the roof edge. Turbulence was found to be more severe, with a thicker turbulence layer, for taller buildings. CFD analysis also showed the roof shape affected wind speed and turbulence. The authors made generalisations from results based on only three separation distances, two building heights and three roof shapes. Roof shape and height are varied simultaneously, making results more difficult to interpret with respect to the impact of one variable on wind speed.

Dannecker and Grant's [24] aforementioned work on wind tunnel testing of wind speeds within ducts was complemented by CFD analysis of wind flow around a building with integrated duct. Due to limits within the CFD software of the number of cells, a simple geometric 90° duct without spoiler was modelled. Free flow wind speed was set at 16.5 ms^{-1}, with turbulence intensity 1%, consistent with wind tunnel tests. Steady-state incompressible flow was assumed, and the authors state that measured and simulated profiles of the wind speed ratio in the duct "show good agreement", although no statistical correlation is provided. Results indicate up to 15% increase in wind speed for this geometry.

Later work by Watson et al. [26] used CFD modelling of straight ducts (spanning the entire building width or half the building width). Unlike other CFD modelling described, the authors used a k–ω turbulence model justified on the basis of one reference which showed this to be more accurate than the alternative k–ε model for diffuser applications. Starting condition wind speed was a uniform vertical profile 5 ms^{-1} wind speed. Contraction ratios, rotor resistance and duct length were varied. Results showed that, when modelling momentum extraction by the rotor as a resistance to flow, high resistance resulted in less flow separation at the base of the duct. Whilst wind speed within the duct was not normalised results do appear to show an increase in wind speed within the duct when compared to upstream wind speed values. Results were shown graphically and described, however relationships between variables such as C_p and K were not derived. The authors focused on comparison of CFD results with simple one-dimensional analysis of flow in ducts, and found that the CFD results showed poorer performance (C_p) than the 1-D mathematical model. The authors found that the building created acceleration of flow and flow separation, which led to differences between the two performance prediction methods.

Grant and Kelly [27] took the mathematical modelling of a ducted wind turbine a stage further by considering one-dimensional flow through a duct, and the power extracted from a turbine placed in the duct. The authors derived a mathematical formula for the power extracted by a ducted wind turbine as shown in Eq. (8).

$$W_{T\,MAX} = \frac{C_v}{3\sqrt{3}} \rho A \delta^{3/2} U_\infty^3 \tag{8}$$

where C_v is the duct velocity coefficient, A is the duct opening area, U_∞ is the free stream wind velocity and δ is the differential pressure coefficient. The power coefficient of the ducted turbine is then as Eq. (9).

$$C_p = \frac{2}{3\sqrt{3}} C_v \delta^{3/2} \tag{9}$$

The authors used building simulation tool ESP-r to obtain differential pressure coefficients, and also manipulated the wind speed data in the climate file, to produce an estimate of annual power output of a ducted wind turbine. Note that the probability density function for wind speed velocity components was assumed to follow a normal distribution, although this was not clearly justified within the paper. Turbulence intensity I formed part of the equation for probability density function, as shown in Eq. (10).

$$f(u) = \frac{1}{IU_\infty\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{u-\bar{u}}{IU_\infty}\right)^2\right] \tag{10}$$

Therefore, wind velocity components u and v were estimated based on the hourly average wind speed, with an assumed value of local turbulence intensity and a normal distribution. Results from the mathematical model indicate turbulence intensity has a significant impact on estimated annual ducted turbine power output, output 59% greater for I = 30% compared with I = 5%.

Further results using this same mathematical approach [28] showed that the turbine power coefficient C_p can exceed the Betz limit for ducted wind turbine applications.

CFD modelling investigations have generally used one upstream wind speed value with a uniform vertical distribution. Typical investigations look at building geometry and the effect on wind speed in the steady state. Results indicate that wind speeds in the "urban" modelled environment are lower than the upstream wind speed. CFD modelling has also shown that wind shear is reduced at the roof edge in "urban" environments, and that wind speeds can increase in ducts. Findings on wind shear, wind speed in ducts and general suppression of wind speed in urban environments are consistent with the results of wind tunnel experiments.

3. Urban wind power production

As explained in Section 2.1 the instantaneous power production from a wind turbine is proportional to the cube of the wind speed. In addition to an understanding of wind speeds in the urban environment, an estimate of potential energy output from urban wind turbines requires analysis of the power production characteristics of the turbine. Research regarding these issues is reviewed in this section.

3.1. Wind speed estimation

Wind data analysis for micro-wind applications has, in the main, used meteorological data in urban areas, due to a lack of in situ data. Several methods exist for deriving wind speed data for specific sites based on measured data from other locations. Landberg et al. [29] provides a useful overview of methods for estimating wind speed, including:

- Measurement (frequency of measurement and averaging methods can affect final estimates of power output [30]).
- Measure-correlate-predict (take a small set of local measurements, correlate to local, regional or national longer time series data, then use correlation to predict forward the local wind speed).
- Wind atlas data (as referred to in [31], see below).

In addition, a database of annual average wind speed in the UK, based on 1 km^2 resolution and using a methodology which removes the effect of surface roughness, is available in the UK. Known as NOABL and made available by the UK Government, this database of annual average wind speeds is less appropriate for small-scale urban wind development but is, nevertheless, occasionally used for this purpose. Several authors have made comparison between the NOABL database and site wind speed data [31–34], and found that the NOABL value of annual average wind speed is higher than the annual average calculated from site measurement.

Herbert et al. [35] provided a review of the use of Weibull and Rayleigh frequency distribution functions in particular, for the estimation of wind resource.

In comparing results of wind speed studies, differences in methodologies of data analysis can be significant. Makkawi et al. [30] asked highly appropriate research questions in investigating the effect of sampling frequency on averages, and the difference between in situ and Met Office data. Based on six months of wind speed data (measured in one dimension) sampled at a two second frequency, marked differences were identified in the cumulative frequency of wind speed when comparing a four second mean, one minute mean and one hour mean. The measure used for consideration of the impact of sampling frequency on the mean was the root mean square difference (RMSD). When compared to the 4-s mean, the 1-min RMSD was slightly less than the 1-h RMSD, although the reader is left to derive from the data whether the difference in 1-min and 1-h RMSD values is statistically significant. The authors also made comparisons of in situ measured data with published Met Office data recorded at Edinburgh airport over a seventeen year period. Whilst cumulative frequency was shown for wind speeds at the two sites there was very little statistical comparison undertaken between the two data sets. The in situ data shown was taken in October 2007 and January 2008, whereas the Met Office data for October and January was based on seventeen years of data, averaged for those months. There is no discussion of the potential influence which this difference in data source has on the analysis (i.e. whether the in situ period represents a more or less windy year compared with the seventeen year average). The authors presented no clear recommendations from their study with respect to appropriate sampling frequency and averaging, or correlation between in situ measurement and available Met Office data.

Allen, Hammond and McManus [36] used turbulence intensity to scale hourly mean wind speed. The authors used Met. Office data, and made no height adjustment. Turbulence intensity resulted in an adjustment to estimated wind speed of 15% in rural locations and 50% in urban locations. The justification of these turbulence intensity factors was absent from the methodology. The estimated wind speed which resulted from the scaled Met. Office data was then used to estimate power production of a micro-wind turbine, using manufacturer power curves and scaled by 90% to account for availability (the 90% availability was not justified by the authors). The authors recognised that the turbulence scaling factor was only applied, in industry, to scale down (and not scale up) the hourly mean wind speed. They also recognised the limited understanding of the extent to which micro-wind turbines could respond to and thereby extract energy from short-lived turbulence. The authors openly state that the method utilised was in need of validation for micro-wind applications.

Met Office and NOABL data is available for the UK and, as shown later in Section 3.4, several authors make use of the data in estimations of urban wind energy generation. There is a gap in the research literature with regard the accuracy of monthly or annual averages from these sources when compared with in situ measurements of greater time resolution, over long sampling periods of several months.

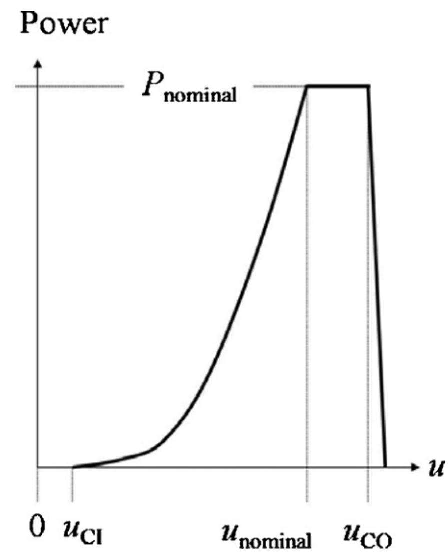

Fig. 2. Simplified power curve, showing cut-in (u_{ci}), cut-out (u_{co}) and nominal ($u_{nominal}$) wind speeds, and nominal power output ($P_{nominal}$).

3.2. Theoretical power curves

Wind turbine output is characterised by manufacturers by a power curve, which shows the power generated by a device over a range of wind speeds (see Fig. 2). Since many calculations of power output combine the power curve information with wind speed distributions, the accuracy of the power curve can have a significant influence on the accuracy of annual power generation estimates. Where manufacturer power curves are not available, estimates of the shape of the power curve can be made based on Eq. (11), for horizontal axis wind turbines.

$$\begin{aligned}
&\text{For} \quad u < u_{ci} : P_{turbine} = 0 \\
&\text{For} \quad u_{ci} \le u \le u_{nominal} : P_{turbine} = P_{nominal} \frac{u^2 - u_{ci}^2}{u_{nominal}^2 - u_{ci}^2} \\
&\text{For} \quad u_{nominal} \le u \le u_{co} : P_{turbine} = P_{nominal} \\
&\text{For} \quad u > u_{co} : P_{turbine} = 0
\end{aligned} \tag{11}$$

In predicting power output from a wind turbine, a common approach in the literature is to take the power curve provided by the manufacturer and combine it with a wind speed frequency distribution function, such as a Weibull distribution (Eq. (12)) or

Rayleigh distribution (Eq. (13)) and integrating across the range of wind speeds in which generation takes place (Eq. (14)).

$$f(u) = \frac{b}{u_c}\left(\frac{u}{u_c}\right)^{b-1} \exp\left(-\left(\frac{u}{u_c}\right)^{b}\right) \tag{12}$$

where b is a shape factor and u_c is a scale factor, both specific for the site.

$$f(u) = \frac{\pi u}{2\bar{u}^2} \exp\left(-0.25\pi\left(\frac{u}{\bar{u}}\right)^{2}\right) \tag{13}$$

where $\bar{u}$ is the local annual average wind speed.

$$\bar{P}_{turbine} = \int_{u_{ci}}^{u_{co}} P_{output}(u) \times f(u)\,du \tag{14}$$

where $P_{output}(u)$ is the instantaneous power output at wind speed u (usually taken from the power curve), $f(u)$ is the frequency of wind speed u (from an appropriate wind speed distribution measurement or estimate, for a specified period of time) and $\bar{P}_{turbine}$ is the estimated average output for the wind turbine over the same specified time period (normally 1 year or 1 month).

A simpler approach to wind turbine power estimation is to use capacity factors, as shown in Eq. (15).

$$\bar{P}_{turbine} = P_{nominal} \times C_F \times t \tag{15}$$

where $P_{nominal}$ is the power output at nominal or rated operation, C_F is the capacity factor, and t is the time period over which the average power output $\bar{P}_{turbine}$ is estimated (typically one year, $t = 8760$ h).

3.3. Analysis of turbine performance for micro-wind turbine applications

Wind turbine machines are typically categorised as vertical axis wind turbines (VAWTs) or horizontal axis wind turbines (HAWTs). A comparison of the two types can be found in Eriksson et al. [37]. Much historical development of wind turbine technology has focussed on HAWTs, although VAWT machines may be more appropriate to the urban scale according to Eriksson et al. [37] due to yaw, nacelle, blade construction, power control, aerodynamics and noise issues.

Some researchers have focused on the engineering challenges of small scale or building integrated wind turbines. Müller et al. [38] derived a mathematical model for the power output of a VAWT based on a design found in the Sistan region of Iran. This simplified model, based on pressure differentials across the design cross-section, achieved theoretical efficiencies (based on fluid flow theory) of 48–61%. Scheurich [39] used CFD to investigate small-scale vertical axis wind turbine designs with straight and with helically twisted blades. Analysis showed that each blade rotating to the downstream side encounters wake from the upstream blade. This resulted in fluctuations in torque coefficient C_Q. The CFD model predicted much greater fluctuations in torque coefficient for the straight blade machine compared with the helically twisted blade machine, which Scheurich [39] stated has implications for loading, vibration and efficiency. This brief conference paper did not provide details of the CFD model parameters.

Ebert and Wood [40] investigated starting behaviour of a small (2 blade, 5 m diameter, 5 kW) wind turbine. Field measurements were taken at a frequency of 10 Hz. There was a range of wind speeds (u) for which blades idled but did not begin to generate. Rotation speed can reach levels high enough to enable generation for short and long duration wind speeds. Therefore short duration gusts could result in wind speed u above cut-in. This starting behaviour is of particular interest for urban applications since typically higher turbulent intensity I could result in short term gusts to assist starting. The turbine was then shown to continue to produce power even if wind speed u decreased, demonstrating a difference in cut-in and cut-out at low wind speeds. The start up time T_s was around 11 s at wind speed $u = 8\ \mathrm{ms}^{-1}$ starting from stationary, rapid acceleration followed by an idling period, then further acceleration to a final rotor speed of 50 rpm at which point the alternator's field current was switched on and the turbine started to generate power. Ebert and Wood [40] found longer idling times at lower wind speeds (25 s idling at $4\ \mathrm{ms}^{-1}$). Clausen and Wood [41] further reported a 50 s start for a larger 16 kW machine to reach operational rotor speed of 300 rpm. The authors recommend improvements in the blade material and manufacture to reduce weight and therefore lower rotational inertia to assist starting. Both papers analysed a relatively small amount of data to derive these conclusions.

Wright and Wood [42] completed further analysis of starting behaviour based on 160 data sets for a 3 blade 2 m diameter 600 W machine. Methodology of measurement and accuracy is well described in the paper. The average start time (from rest up to 250 rpm) of the machine was 28 s, and the average starting wind speed u_s was $4.6\ \mathrm{ms}^{-1}$, but the start time was shown to be strongly dependent on wind speed as per the findings of Ebert and Wood [40]. The relationship was shown to have the form $T_s \sim u^{-2}$. Analysing the data further and using 15 s periods of relatively steady wind speed u, the authors found the cut-out wind speed to be around $2.5\ \mathrm{ms}^{-1}$ or less, which again is in agreement with the findings of Ebert and Wood [40] but based on a larger data set. With a high rotor speed Ω, a drop in wind speed u produces a low angle of attack α and hence sufficient lift:drag ratios to enable continued generation even at low wind speeds.

Wang et al. [43] undertook a complex analysis of power output from a theoretical turbine design. The rotor and a scoop design were analysed in CFD assuming incompressible steady-state flow, Navier–Stokes relationships and a k–ε turbulence model. Predicted pressures were then used to determine annual power output for measured wind speed data at a site in Edinburgh (hourly wind speed averages, period of measurement and methodology unknown). The authors made comparison of their design with two other machines of similar swept area. The design with scoop was estimated to produce more energy annually than the two comparison machines. Using a Weibull function rather than measured wind speed data led to much higher power output estimates. However, this may be because the measured wind speed data did not represent a good fit to the Weibull distribution function.

Research has therefore found that the starting behaviour of standard HAWT designs is complex and that gusts can assist starting. This further supports the need for wind speed data of an appropriate time resolution, to enable estimated wind turbine output to consider short-term fluctuations in wind speed. In addition, some research has shown improved performance at low wind speeds for amended wind turbine designs (VAWTs, helical twisting of blades, scoop design).

3.4. Estimation of wind speed and power production

Considering capacity factors as an approach to turbine output estimation (Eq. (15)), early work by Abed and El-Mallah [44] investigated the theoretical derivation of capacity factor C_F for wind generation. The authors found that C_F increased with average wind speed $\bar{u}$. This finding was confirmed in a study by Khalfallah and Koliub [45,46] using observations of wind speed and wind turbine output recorded over a number of years.

Bishop and Amaratunga [47] used rotor diameter to estimate power production, based on wind speed data and derived Weibull parameters. Their theoretical analysis of a 10 MW wind farm compared with an equivalent 10 MW capacity of distributed small scale Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind

Turbines (VAWTs) found that predicted power production was higher for the 10 MW wind farm than the 10 MW of distributed small machines, and that the HAWTs performed better than the VAWTs with respect to power production. It is not clear how the authors accounted for turbine rated power output characteristics.

Garcia-Bustamante et al. [48] used the approach shown in Eq. (14), using hourly wind speed distribution data. Based on observed wind speed and power output data from five wind farms, the authors derived an observed frequency distribution $f(u)$ and an effective power curve (EPC). This approach was then compared with estimated power outputs based on a Weibull wind speed frequency distribution. Analysis of P_{observed} with P_{weibull} showed that use of the Weibull function resulted in an underestimation in power output, to a maximum difference on one site of 10.3%. Consideration of χ^2 as a measure of fit of $f(u)_{\text{weibull}}$ to $f(u)_{\text{observed}}$ showed the Weibull distribution to be a relatively poor approximation of the measured data. The overall impact of use of Weibull was an underestimation in the total energy generation at the investigated wind farm sites. In later work, the same authors [49] compared estimated power outputs based on different versions of the power curve. These were an effective power curve (EPC – the measured data), a theoretical power curve (TPC – the manufacturer's data), an average power curve (APC – an average of the EPCs over the observation period for each site) and a polynomial fit curve (PFC – a cubic polynomial that is a better fit to the EPC values). When compared with P_{observed} the authors found the EPC method the most accurate, the TPC method tended to overestimate and the PFC tended to underestimate power output. The work in these two papers represents a very comprehensive analysis of the sources of errors in estimates of power output, and should data of the same resolution be available for small-scale wind turbines it would be a highly relevant addition to the literature to apply the methodology of Garcia-Bustamante et al. [48,49].

Rankine et al. [31] used a Rayleigh distribution analysis (see Eq. (13)) based on mean wind speed, combined with the manufacturer's power curve, to make an initial estimate of annual output of a particular make of micro-wind turbine (1.5 kW "SWIFT"). The authors calculated that manufacturer claims of "typical" annual output would require annual average wind speeds of 5.5–6.3 ms^{-1}. The authors then analysed the carbon and energy paybacks based on a wide annual production range of 1000–4000 kWh, corresponding to annual average wind speed in the range 4–7.2 ms^{-1}. This choice of range of wind speeds is not well justified by the authors, particularly since their own analysis would suggest wind speeds in typical UK urban locations of less than 4 ms^{-1}. The same approach was taken by Mithraratne [50] in an analysis of energy and carbon paybacks for the SWIFT machine for applications in New Zealand. However, the author used a far simpler estimation of power production based on capacity factor and mean wind speed, and the uncertainty in the estimation method was not quantified.

Peacock et al. [33] also use the approach of power output estimation based on wind speed distribution and power curves (Eq. (14)). Estimated power output was based on observed wind speed data for two years of a 10 min time resolution, for two sites – each site having one calendar year of data. Where measurements were missing, the authors copied data from previous days. Measurements were taken at 2 m above ground level (AGL) and adjusted to 10 m AGL using Eq. (16). Without reference to alternative wind speed measurements over the two years (2000 and 2001) and with a lack of information about the two measurement sites, it is unclear whether the difference in annual average wind speed is primarily due to differences in wind speeds generally for the two years compared, or due to differences in the sites. The authors have assumed the latter, describing one site as "low wind speed" and the other as "high wind speed". No explanation is given for this assumption and no discussion of results refers to the two sites being measured over two different periods. The authors briefly refer to the annual average wind speed for the two sites and make limited comparison (no statistical analysis) with annual average wind speed for the location as stated in the NOABL database (values are unadjusted for surface roughness). Power curves were used in combination with wind speed, to estimate power output. The power curves used were based on available information from manufacturers, for four turbines. For the "low wind speed" site ($\bar{u} = 2\ \ \text{ms}^{-1}$) the authors found that power production did not take place for 51–70% of the year due mainly to wind speeds being below u_{ci}. For the "high wind speed" site ($\bar{u} = 4.9\ \ \text{ms}^{-1}$) the period of non-generation was reduced to 25–37% of the year. Data on the predicted annual generation for the two sites, two years and four turbines is not provided in sufficient detail to enable further discussion here. The authors go on to consider demand matching based on nine dwellings with electrical demand profiles of a 1 min time resolution.

$$v_z = v_{ref} \times \frac{Ln(z/z_0)}{Ln(z_{ref}/z_0)} \tag{16}$$

where v_z is the wind speed at height z, v_{ref} is the wind speed at the reference height z_{ref}, and z_0 is the roughness length.

Turan et al. [34] had previously shown an estimation of wind turbine power output (2.5 kW machine) using measured and NOABL wind speed data for nine sites. This earlier work used the same methodology of manufacturer's power curves and annual mean wind speed (see Eq. (14)), although it was not specified whether a Rayleigh function was used to derive the wind speed distribution for estimation of power output. Using the data provided in Turan et al. [34], for eight sites (the ninth data set was discounted since hub height data was incomplete), a brief analysis has been completed. Note that NOABL values were not adjusted for surface roughness since this information was not provided in the research [34]. Comparing $\bar{u}$ (measured) and $\bar{u}$ (NOABL), the $\bar{u}$ (NOABL) was higher for all eight sites, on average 55% higher (standard deviation 23%, range 17–82%). Comparing $\bar{P}_{turbine}$ (measured) and $\bar{P}_{turbine}$ (NOABL), the $\bar{P}_{turbine}$ (NOABL) was on average 239% higher (standard deviation 129%, range 41–428%). The difference in C_F was similar to that of the difference in power output $\bar{P}_{turbine}$, the C_F (NOABL) was on average 236% higher (standard deviation 128%, range 42–421%). Whilst the analysis of Turan et al. [34] was based on manufacturer's power curves and a theoretical wind speed frequency distribution function, rather than measured power curves and measures wind speed frequency distribution, it does highlight the extent to which NOABL wind speed data can lead to significant over estimation of wind turbine power output.

For a detailed analysis of energy payback, Crawford [51] estimated power production based on wind speed distribution and power curves (Eq. (14)). For the two machines analysed, the author used manufacturers' power curves with measured wind speed for two locations. The author does not provide sufficient information to determine the frequency of wind speed measurements or height of measurement AGL, but states in assumptions that a Weibull wind speed distribution function was assumed.

Power output estimation based on wind speed distribution and power curves (Eq. (14)) has been used by Underwood et al. [52]. In estimating the wind turbine power generation, the authors used the method described in Eq. (11) to determine theoretical power curves. Wind speed data was derived from the local annual average wind speed and a distribution function calculated from a UK IWEC (International weather for energy calculations) data set, rather than the Rayleigh or Weibull distribution.

Bahaj et al. [53] created a numerical modelling software tool to estimate wind turbine power production for small turbine sizes. Wind speed and direction comprised yearly sets of 30 or 60 min averages for 9 UK sites, the source and error of which was unspecified. Wind data was then adjusted based on user assumptions of hub height and terrain roughness, although there is no detail of the adjustment method other than that it used “Prandl boundary layer theory” [53]. The authors did not use manufacturer’s power curves but instead derived C_p from commercial turbine design software and used this to estimate power output, based in the relationship shown in Eq. (17) (a rearrangement of Eq. (10)).

$$C_p = \frac{2P_{turbine}(u)}{\rho A u^3} \tag{17}$$

Bahaj et al. [53] provided a two case study comparison of the sensitivity of the software tool to hub height and average wind speed. Further functionality of the software enables users to specify wind shadow effects, estimate demand matching and identify potential financial and carbon savings.

The comprehensive wind tunnel investigation of roof-mounted wind turbine installation locations by Blackmore [22,23] described above in Section 2.3 was used in Phillips et al. [32] in their estimation of wind power production. The authors analysed Meteorological Office data for three weather stations using BREVe software to establish the effect on measured wind speed of local topography and surface roughness. Urban locations close to the Met Stations were also analysed in BREVe and the authors produced scaling factors for velocity based on the BREVe results for each, based on Eq. (18).

$$S_v\left(\theta\right) = \frac{V_c\left(\theta\right)}{V_o\left(\theta\right)} \tag{18}$$

where $S_v(\theta)$ is the wind velocity scaling factor for wind direction θ, $V_c(\theta)$ is the hourly mean wind speed at the location for wind direction θ and $V_o(\theta)$ is the hourly mean wind speed at the Met Station for wind direction θ.

Similarly they derived scaling factors for power, given that power is related to the cube of the wind speed. This power scaling factor is shown in Eq. (19).

$$S_p\left(\theta\right) = \frac{V_c^3\left(\theta\right)}{V_o^3\left(\theta\right)} \tag{19}$$

Once the scaling factor was determined for urban roughness (Eq. (18)), this and a further scaling factor based on the work by Blackmore [23] to account for the effect of the building was applied to Met Office wind speed frequency distribution. Using the adjusted wind speed and available power curves (source not specified) the authors then calculated the power production (as per Eq. (14)) for three UK locations, based on four possible roof mounting positions and four arrangements of adjacent buildings. Results showed the lowest power generation for turbines mounted close to the eaves and for building locations in the city centre. Phillips et al. [32] recognised that the results could be considered optimistic since the calculations did not allow for turbulence effects.

As the above review shows, a significant number of authors have chosen an approach to power production estimates based on Eq. (14), which requires knowledge of the wind speed frequency distribution and wind turbine power curve, or methods to estimate these. Garcia-Bustamante et al. [48,49] provide a comprehensive analysis of the impact of Weibull and power curve on estimated energy production, for large wind turbines installed in wind farms. Many authors have used a Rayleigh distribution function to estimate wind energy for a particular location. Further analysis of the use of wind speed distribution functions and their effect on estimated wind energy production is necessary, for small wind turbine applications in urban locations.

Of the work reviewed, Phillips et al. [32] considered the effect of the wind turbine mounting position relative to the building. This work, based on wind tunnel tests, would benefit from further analysis through in situ measurement and CFD analysis. In addition, further work is needed regarding use of scaling factors based on wind speed data of high time resolution (to ensure consideration of turbulence is incorporated).

For the UK, an energy performance prediction methodology has been outlined in the Microgeneration Installation Standard MIS 3003 [54]. The MIS3003 is intended to be used by Microgeneration Certification Scheme (MCS) Registered Installers. The standard recommends that power production be estimated from NOABL wind speeds, adjusted by a scaling factor, and manufacturer “annual energy performance curve”. Scaling factors vary with distance from the building roof ridge to the lowest point on the turbine blades. The scaling factors are to be applied to NOABL data, whereas the scaling factors produced by Phillips et al. [32] are to be applied to Met Office data and do not vary with height. This makes comparison difficult, however the Phillips et al. wind speed scaling factor for the city centre of Manchester (approximately 0.57) is similar to that in MIS3003 wind speed scaling factor of 56% for dense urban at a ridge-blade tip separation of 10 m. The original source of information on scaling factors referenced in MIS3003 is now 20 years old.

3.5. Measurement of power production

A comprehensive contribution to public domain data on small scale wind power production has been made by Encraft in their funded study known as Warwick Wind Trials project. Several reports have been produced during the project, and this review draws primarily on the final report [55]. 26 sites were monitored for wind speed, energy generation and energy consumption (consumption primarily due to the inverter) every 10 min. Wind measurements were analysed for variance with NOABL predictions, with NOABL values shown to be greater than measured values at all sites, more than 40% greater at 16 sites, and up to a maximum 70% greater. NOABL values were also scaled using the appropriate factors from MIS3003 and compared with measured wind speed. This improved agreement somewhat, with 19 sites having predicted wind speed within 40% of measured wind speed. Wind measurements were also analysed for Weibull fit and it was found that a shape factor k of 1.56 (average for all sites) gave a better fit than the standard k value for the UK of 2. No details were provided in the report of the period over which measurements were taken, how missing data was treated, or the accuracy of the measurement equipment. No comparison was made with available Met Office data for the same period and similar location, or with standard weather data for the UK. It is therefore unclear, when determining the overall potential for wind power in urban locations, whether the study happened to monitor a period which was more or less windy than average.

With regards measured energy output, this varied from output predicted using measured wind speeds. Overestimation of a factor of 1.7–3.4 was hypothesised by the authors to be due mainly to the accuracy of the turbine power curves, as well as the accuracy of the wind speed measurements and the response time of instrumentation and turbines. In producing power curves based on measured wind speed and power output, Encraft [55] found that measured power curves were in closest agreement with manufacturer power curves at low wind speeds. For all measured power curves, the power output at low wind speeds was lower (in most cases much lower) than power output predicted from manufacturer power curves. Capacity factors were also considered by the authors, but averages given have been calculated for an unspecified time period, without standard deviations. Details regarding the measurement accuracy, and calculations such as the standard deviation of averages, are also missing from the discussion of wind speed data, and therefore the reliability and accuracy of the work is unclear.

Nagai et al. [56] compared measured and theoretical performance of a 3 kW roof mounted wind turbine. Data was sampled on a 1 s basis but a relatively small amount of data from 1 day in January and 2 days in March is provided in the paper, and conclusions inevitably cannot be drawn for annual performance. For example, actual generation is compared to predicted, over a range of wind speeds, for a 1 h period and conclusions drawn by the authors as to the measured energy production exceeding predicted at low wind speeds, and measured energy production being lower than predicted at high wind speeds. The predicted energy output was based in the calculated capacity factor for the 1 h period.

Parcell [57] collected energy generation data (instantaneous power and cumulative energy) and wind speed data from one site over a three month period. Wind data was averaged into 1 min readings. The author calculated Weibull coefficients (shape factor and scale factor) based on the measured wind speed data, and compared the measured wind speed distribution with the Weibull and Rayleigh distribution predictions for each month. The Weibull function was found to give a better overall fit to the data based on the derived coefficients. A comparison of instantaneous power output (as a function of wind speed) with the manufacturer's published power curve indicated that measured output was lower than predicted for wind speeds below 14 ms^{-1}. The author provides a discussion of losses, response time, load resistance and inverter behaviour contributing to a discrepancy between the measured and manufacturer power curve.

Parcell [57] compared measured instantaneous power production against predicted using two methods. The swept area method (Eq. (10)) underestimated power production, when using the arithmetic mean wind speed. However, Parcell [57] proposed that the wind speed at which mean power production occurs would be a more appropriate value. Deriving this wind speed at which mean power production occurs from Weibull coefficients, results in Eq. (20).

$$u(\bar{P}_{turbine}) = c\Gamma\left(1+\frac{1}{k}\right)$$
$$\text{where} \quad \Gamma(1+x) = x\,\Gamma(x) \tag{20}$$
$$\text{and} \quad \Gamma(x) = \sqrt{2}\pi x x^{x-1} e^{x}\left[1+\frac{1}{12x}+\frac{1}{288x^2}+\dots\right]$$

where $\Gamma(x)$ is the Stirling approximation of a gamma function Γ.

Using the power curve method (Eq. (14)) Parcell found that predicted energy production exceeded measured energy production, when using the manufacturer power curve and a Weibull wind speed distribution with shape and scale factors derived from published wind speed data (Chartered Institute of Building Services Engineers (CIBSE) Test Reference year (TRY) wind speed data). Using a power curve derived from instantaneous power output data, and Weibull factors derived from measured wind speed data, the author found predicted energy output was closer to measured energy production when compared with the swept area method, for two of the three months analysed. These two methods (and their refinements) were not analysed statistically for variance from measured values.

When looking at measured power production, the studies reviewed have found that wind energy estimation methods are not accurate. Encraft [55], in applying the MIS3003 [54] methodology, found wind speed estimation within 40% of measured wind speed for 19 sites but an overestimation of energy generation by a factor 1.7–3.4. Nagai et al. [56] and Parcell [57] used different methods but both found poor correlation between predicted and measured energy generation. Parcell's finding that estimation accuracy was improved when based on a measured power curve is consistent with that of Garcia-Bustamante et al. [49].

Table 1
Scaling factors from MIS3003 (used to scale NOABL mean wind speed values for a height 10 m AGL, for a turbine mounted less than 10 times the height of the upwind obstruction or mounted directly on buildings) [54].

	Distance to ridge from lowest point of turbine blades (m)	Mean wind speed scaling factor
Dense urban: City Centre, mostly closely spaced 4 storey buildings or higher, average ridge height 15 m AGL	10	56%
	5	51%
	3	44%
	1	35%
Low rise urban/suburban: typical town/village with buildings well spaced, average ridge height 10 m AGL	6	67%
	4	61%
	2	53%
	0	39%
Rural: Open country with occasional houses and trees, average ridge height 10 m AGL	12	100
	7	94
	2	86
	0	82

Table 2
Scaling factors from Phillips et al. (used to scale Met Office mean wind speed values for a height 10 m AGL, no specification regarding turbine mounting) [32].

	Mean wind speed scaling factor (%)
Manchester	
Location 1: south east edge	63
Location 2: north west edge	60
Location 3: south west edge	58
Location 4: north east edge	60
Location 5: city centre	57
Average of all 5 locations	60
Portsmouth	
Location 1: south east edge	101
Location 2: north west edge	83
Location 3: south west edge	92
Location 4: north east edge	113
Location 5: city centre	63
Average of all 5 locations	90
Wick	
Location 1: south east edge	103
Location 2: north west edge	100
Location 3: south west edge	65
Location 4: north east edge	104
Location 5: city centre	65
Average of all 5 locations	87

4. Conclusions

This review of the literature has shown that the dominant methodology for estimation of power output for small-scale turbines is that of Eq. (14), using the power curve of the turbine and a wind speed frequency distribution. This methodology is flawed for the urban small-scale wind turbine application for several reasons.

1. Simplified power curves such as shown in Eq. (11) and used by Underwood et al. [52] are not appropriate for all turbine types. The shape of the power curve does vary with pitch control method and the simplified power curve is likely to be more inaccurate at high wind speeds.
2. Manufacturer power curves are produced without reference to any clear standard for the method of production. As shown by Garcia-Bustamante et al. [49] a comparison of manufacturer power curves and effective power curves (directed from turbine power production data) shows the manufacturer power curve generally underestimated power output at low wind speeds and overestimated at high wind speeds. Limited data in the Encraft study [55] did show effective power curves best matched manufacturer power curves at low wind speeds, but that the use of manufacturer power curves led to overestimation of energy output. Parcell [57] also found power output to be lower than that predicted using manufacturer power curves, for a small data sample. Whilst the methodology of Garcia-Bustamante et al. [49] is rigorous, it is applied to wind farm data rather than small-scale wind turbines. The approach taken by Encraft [55] is less rigorous in its reporting and the study by Parcell [57] is very limited due to its extremely small sample size. None of the reviewed literature then identified the error associated with using effective power curves from one site for the same machine installed in a different location. Therefore, no author has demonstrated the application of effective power curves on any site other than the site for which the effective power curve was derived. As a result, there is a need for rigorous research into effective power curves for small-scale wind turbines, which analyses the error associated with the use of effective power curves for multiple locations.
3. In some cases, the reviewed literature has derived wind speed frequency distribution using Weibull or Rayleigh distribution. In other cases, authors used Met Office data or NOABL data. Where wind speed data was actually recorded at site, very little analysis of measurement error has been reported. There is a lack of reporting of errors in measured or derived data, which therefore leaves the reader uncertain as to the degree to which the discrepancy between predicted and actual energy output is due to errors in predicted wind speeds. Garcia-Bustamante et al. [49] did undertake a more rigorous approach to their analysis of predicted energy output, and reported predicted energy output based on three different power curves. However, this analysis did not investigate further the impact of error in wind speed frequency distribution. Whilst the authors used on site wind speed measurements, there was no reported error in measurement, or consideration of the impact on accuracy of the use of hourly wind speed averages. Therefore, there is a need for rigorous research into wind speed frequency distributions for small-scale wind turbines, which analyses the error associated with measured data, the use of time averaged data and Weibull or Rayleigh distributions. This analysis must consider the impact of wind speed data of an appropriate time resolution to enable consideration of the effect of short-term gusts and other turbulence effects.
4. The review provided in Section 3 demonstrates the complexity of estimating the potential for urban wind turbines. Small scale applications of wind turbines in the urban environment are likely to involve sites where wind speed measurement over a twelve month period is prohibitive for time and cost reasons. However, Met Office data may be more readily available to installers/developers. For the potential end user, particularly the domestic sector, the NOABL database is a public domain data set and therefore easy to access. As the work of Phillips et al. [32], Parcell [57] and Encraft [55] showed NOABL and Met Office annual average wind speed data to be inaccurate when compared to measured wind speeds for specific sites, a practical alternative for the small scale application would be the use of scaling factors with NOABL or Met Office wind speed data. Scaling factors from Phillips et al. [32] and the MIS3003 [54] are shown in Tables 1 and 2. Further work is needed to update the MIS3003 scaling factors, which are based on work undertaken in 1980. Whilst the methodology taken by Phillips et al. [32] could be applied (i.e. the use of BREV-e software to estimate impact of topography and surface roughness) it is vital that future work considers the accuracy of the methodology by comparing with measured wind speed. The rigorous analysis of urban wind speeds, reviewed in Section 2, using measurement, CFD and wind tunnel testing, assists in the estimation of urban wind speeds and further work in this area could lead to improvements in scaling factors.
5. Work by Parcell [57] would indicate that the wind speed at which mean power production occurs would be a more appropriate wind speed value than the mean wind speed, for estimation of instantaneous power output. A more detailed analysis of this hypothesis would be a useful addition to the literature.

The UK Coalition Government is currently (Autumn 2010) undertaking a consultation on the microgeneration strategy [58]. At present, small-scale wind is one of the technologies eligible for support through the feed-in tariff scheme [11]. Schemes of 50 kW or less installed capacity must be installed under the Microgeneration Certification Scheme (MCS) [59]. For robust advice to be given to home owners by MCS registered installers, it is vital that methodologies for estimating potential output from a small scale wind turbine are provided with a health warning – an understanding of their accuracy, the level of error, and the source of error. Without these improvements in methodology, the technology may be labelled uneconomic when in effect it is being installed in inappropriate locations.

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