Measured wind and morphological characteristics of a peri-urban environment and their impact on the performance of an operational large-scale wind turbine

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A R T I C L E   I N F O

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A B S T R A C T

The market for single medium and large-scale wind turbines deployed at industrial consumer sites has future expansion potential, due to evolving electricity systems from centralised to distributed. Many industrial sites have low-rise buildings, typically found in peri-urban environments, such as at the edge of towns and cities. Unlike rural onshore wind farm sites, peri-urban wind environments can have more complex wind regimes with respect to turbulence, wind shear and gusts. The resulting wind conditions may influence a wind turbine’s energy performance and have turbulence characteristics that exceed current international turbine design standard specifications. These conditions can give rise to extra challenges in wind turbine micro-siting and reduce turbine operational lifetimes in peri-urban environments. This field study examines the impact of buildings on the wind characteristics and energy performance of an 850 kW wind turbine in a peri-urban environment. A 16 sector directional analysis of long-term SCADA data, onsite LiDAR measurements and measurements from a local rural met mast, combined with a morphological analysis of local buildings show that buildings higher than 20% of hub-height with sector wise plan area fractions greater than 20% are significant. New peri-urban micro-siting recommendations and revisions to IEC standard normal wind turbulence models are suggested.

1. Introduction

Many nations, such as Ireland, have committed to new renewable energy and greenhouse emission reduction targets by 2030 (DCCAE, 2019). As part of these commitments, new energy policies that promote consumer engagement with energy systems and markets present new opportunities for onsite energy generation with renewable energy technologies (DCCAE, 2015; Milcuieni et al., 2019; Brown et al., 2020; Kotilainen, 2020). Distributed wind encompasses small, medium, and the lower end of large-scale wind turbine technology (up to ~ 2 MW), deployed as single turbine or small-scale wind farm projects (DWEA, 2015). The International Energy Agency (IEA) commenced an international wind research Task in 2018 dedicated to distributed wind (Orrell and Baring-Gould, 2018). This reflects a renewed international impetus for the development and deployment of distributed wind systems, particularly as electricity systems and grids evolve from centralised to distributed. Historically, distributed wind has had mixed market success, primarily due to intermittent government incentives as well as technological challenges (Nock and Baker, 2017; Foster et al., 2020). Technological challenges include quality of product for safe operational and economic lifetime longevity, typically for 20 years. It is well known that the wind environment has a major influence on the viability of any wind energy project in terms energy output and turbine wear (Jung and Schindler, 2018, 2020; Byrne et al., 2020). As well as wind speed and direction; turbulence, shear, veer, inflow angle and atmospheric stability can have significant impacts on a wind turbine’s performance (Wagner et al., 2009; Wharton and Lundquist, 2010; Bardal et al., 2015; Wallace, 2015; Rodrigo et al., 2018; Gualtieri, 2019).

Distributed wind projects deployed at the point of electricity use, such as behind the meter, at industrial sites in peri-urban areas, may have complex wind environments due to the influence of obstacles such as buildings and higher surface roughness. Meteorological studies of urban boundary layers show how multiple internal boundary sub-layers can form over cities in the transition from rural to city environments. These can comprise of canopy layers, roughness sublayers and inertial sublayers (Macdonald, 2000; Iheugah et al., 2014; Pelliccioni et al., 2016; Kent et al., 2017; Ricci et al., 2017). The existence and height range of the each layer can vary depending on

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building dimensions, densities and distances from the rural to urban topographical interface, particularly in prevailing wind directions. These can lead to complex wind shear profiles in these environments (Millward-Hopkins et al., 2013). Morphological methods, which describe building spatial patterns, are used in urban canopy wind flow studies, particularly for dispersion of pollutants and wind energy (Macdonald et al., 1998; Millward-Hopkins et al., 2011; Li et al., 2013; Carpentieri and Robins, 2015; Krayenhoff et al., 2015; Castro, 2017; He et al., 2019; Wang et al., 1998). Many studies of wind energy in urban settings, to date, focus on small-scale wind turbines, in particular, building integrated wind systems (Best et al., 2008; Drew et al., 2013; Sunderland et al., 2013). They highlight the complexities of turbulent wind flow above and around building rooftops, which have implications for small wind turbine performance and the need for robust product design in terms of safety and operational life cycle. In contrast, few studies exist of medium to large-scale tower mounted turbines in peri-urban areas, such as at the edge of towns and cities, in the transition regions from rural to urban environments. These areas can be home to large industrial energy users that have potential to offset their electricity costs and greenhouse gas emissions by deploying onsite, behind-the-meter industrial deployment. Therefore operational energy performance and robust design standards are some of the areas requiring further investigation to help enable the expansion of a global distributed wind market, particularly for behind-the-meter industrial deployment.

This measurement based field study examines the wind characteristics and the energy performance of a large-scale wind turbine for the specific case of peri-urban wind environment. The wind turbine studied is a single Vestas V52 that has been operating behind-the-meter since 2005, at Dundalk Institute of Technology (DkIT) in Ireland. Located at the edge of Dundalk town, the turbine site is surrounded by broad low-rise building obstacles ranging in height from 6 m to 25 m and one tall narrow building with a height of 47 m. A combination of multi-annual turbine SCADA data, 1 year of wind measurements from an onsite LiDAR and wind measurements from an offsite rural met mast, located 1.2 km away, are analysed. The directional turbine energy performance, wind turbulence, shear and gust factors are assessed in relation to the morphological properties of building obstacles in 16 directional sectors around the wind turbine site. The validity of current IEC normal turbulence models (NTM), specified for both small and large-scale wind turbines, are tested against the analysed data.

The study begins with a site description and assessment of local building obstacles, using morphological methods, at both the wind turbine and met mast locations. Secondly, the long-term directional energy output, power curves and turbulence intensity at the wind turbine site are assessed from 7 years of time series turbine SCADA data. Wind measurements at 10 m and 30 m at the offsite rural met mast along with wind turbine SCADA data, over a concurrent 7-month period, are used to compare the impact of the building obstacles on energy and turbulence between both locations. Thirdly, one year of LiDAR wind measurements at the wind turbine location, measured at 10 heights from 10 m to 300 m, are used to examine directional wind power density (WPD) at multiple heights, wind shear across the rotor disc, rotor equivalent wind speed (REWS), gust factors, and horizontal and vertical turbulence intensities. Finally, the implications for large-scale wind turbine micro-siting in peri-urban environments and future IEC design standard revisions are discussed. New peri-urban micro-siting recommendations and revisions to IEC standard normal wind turbulence models are suggested.

2. Methods

2.1. Site overview and measurement setup

Dundalk town is situated by the coast in the northeast of Ireland. The DkIT campus is located on the southern side of the town close to the transition from the rural to the urban environment. Fig. 1 shows the
Vestas V52 wind turbine located on the DkIT campus and some of surrounding campus industrial and residential buildings. The turbine is located at 53.983520, −6.3913908. The surrounding rural terrain, within a 20 km radius of the site, is low-lying agricultural land. The majority of the terrain is below 50 m above sea level (a.s.l.) and contains sparse shelterbelts. The coast of Dundalk bay is approximately 3 km to the east of the site. To the north and northeast, approximately 7.5 km away, there are hills that range in elevation from 75 m to 563 m a.s.l.

Fig. 2 shows the local built environment around the wind turbine location. Within approximately 1.1 km radius of the wind turbine there exists a number of industrial buildings. The majority of the buildings, circled in white, range in height from 7 m to 13 m. Circled in yellow is a narrow 47 m high building and a 25 m building circled in red. To the north of the site, the town consists of residential and commercial buildings that are ~6 m–7 m in height.

A ZX dual mode LiDAR is ground mounted, at location (LiD) in Fig. 2, approximately 60 m from the wind turbine location (WT). It can measure wind at 11 user-selected heights from 10 m to 300 m. The process of determining the wind speed and direction values at a given height takes ~1.5 s, therefore, data from all 11 heights are collated every ~16 s. Data is logged in 10-min average values. The chosen location for LiDAR placement was constrained by factors concerning device security and power supply availability. Based on previous studies using the Irish wind atlas at the site, it is known that the dominant general prevailing wind directions are from the southwest and southeast (Byrne et al., 2019). Therefore, buildings from southeast through to the west of the turbine location are of most interest here. A 34 m met mast (M) is located in a rural location approximately 1140 m west southwest of the wind turbine location to capture prevailing south-westerly winds that are less influenced by building obstacles, compared to location WT. The wind turbine and measurement equipment are shown in Fig. 3 and data acquisition details are outlined in Table 1.

The wind turbine SCADA system that collects wind and power data from a nacelle mounted, Thies 2-D ultrasonic, anemometer and power sensors. 10-minute time series data, over 7 years, from the wind turbine SCADA is used to assess the long term directional energy output, power curves and turbulence. The LiDAR transmits and focuses an infra-red laser beam in a 50 point conical scan at the desired level. The Doppler shifted back scattered beam from the moving aerosols in the wind flow is detected and processed in the LiDAR system to give the wind velocity components at the given heights (Gottschall et al., 2012; Branlard et al., 2013). The LiDAR is used to assess directional wind shear, turbulence and gust factors, at 11 heights, at the turbine location from 1 year of continuous measurements. The 11 heights are chosen to capture effects of the buildings of different heights, to make comparisons with measurements the met mast location, to examine wind shear profiles across the rotor disc. In addition, the highest measurement levels of 200 m–300 m are assumed to be high enough not to be influenced by local buildings, where mesoscale influences on the wind climate are more dominant (Britter and Hanna, 2003; Best et al., 2008).

The 34 m met mast is equipped with boom mounted NRG 40C anemometers, NRG 200P wind vanes. The mast measurements were made in period after the LiDAR measurements due to delays in the local permitting process for its installation.

Due to the large number of individual buildings in the area, it becomes impractical or even impossible to assess the influence of every individual building or obstacle, apart from particular standout obstacles. Therefore, a morphological approach is used to describe the building patterns as viewed from both the wind turbine and met mast locations, shown in Fig. 4.

For both the WT and M locations, 16 directional sectors are divided into four segments (regions of interest) of 500 m distances in the radial direction, extending out to 2 km. It is apparent that the sectors and

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**Fig. 2.** Local buildings (Circled: yellow 47 m, red 25 m, white 6–13 m), wind turbine (WT), LiDAR (LiD), Met mast (M). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
segments to the south and west viewed from location M have far fewer building obstacles compared to location WT. In the case of location WT, the 2 km extremity stretches beyond the physical urban-rural interface in the southwest prevailing wind directions. It also covers a distance of approximately 40 times the highest obstacle (47 m), which is well in excess if current siting recommendations of 20 times the highest obstacle and exceeds IEC criteria for obstacle assessments used at accredited wind turbine test sites (IEA Wind, 2018; IEC 61400-12, 2017).

The principal morphological parameters applied the 500 m segments of each sector are defined as follows (He et al., 2019):

The average obstacle height weighted by obstacle plan area $h_{AW}$ is defined by (1).
\[ h_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i} \]  

(1)

where:

- \( h_i \) – height of an individual obstacle \( i \)
- \( A_i \) – plan area occupied by an individual obstacle
- \( N \) – Total number of obstacles

The obstacle plan area fraction \( \lambda_p \) is defined as the ratio of the total plan area occupied by all obstacles to the total surface area in region of interest (2).

\[ \lambda_p = \frac{A_p}{A_T} \]  

(2)

where:

- \( A_p \) – Total plan area of the buildings and obstacles
- \( A_T \) – Total plan area of region of interest

The frontal area density \( \lambda_f \) is a measure of the frontal area per unit horizontal area per unit height (3). Only the portions of the frontal area of obstacles that are in view in a given direction are considered. i.e. any portions of the frontal area of obstacles masked by other obstacles are not included.

\[ \lambda_f(z, \theta) = \frac{A(\theta)_{proj(\Delta z)}}{A f \Delta z} \]  

(3)

where:

- \( A(\theta)_{proj(\Delta z)} \) is the area of building surfaces normal to a given wind direction \( \theta \) and height increment \( \Delta z \)

All area and the building height information is obtained from the 3D Buildings feature of Google Earth Pro.

### 2.3. Energy assessment

The long-term, 7 year, directional energy output in kWh, in 16 directional sectors, from wind turbine SCADA data is determined using an electrical energy rise (EER) described by (4) and (5) (Byrne et al., 2018).

For a given directional sector \( k \) of width \( \Delta \theta_k \), the electrical energy is expressed as summation of the product of average power values \( P(T)_{jk} \) and 10-min averaging time period \( T \).

\[ E_k(\Delta \theta_k) = \sum_{j=1}^{N_j} P(T)_{jk}(\Delta \theta_k) \times T \]  

(4)

\[ \text{EER}_k = \sum_{j=1}^{N_j} E_k(\Delta \theta_k) \]  

(5)

where:

- \( N_j \) – number of points in data set \( j \) in sector \( k \)
- \( N_k \) – number of sectors

In this case, the sector width \( \Delta \theta_k \) is 22.5°, giving \( N_k \) a value of 16. The \( P(T)_{jk} \) values have units of kW and timestamp period is 10 min or 1/6 h to give EER values in kWh. The building obstacles in the higher energy sectors are of most interest in this study. Binned directional power curves, power standard deviations and turbulence intensity are produced for those sectors of interest. Low energy sectors in non-prevailing wind sectors are not considered in detail. The binned directional power curves with hub-height wind speed are obtained using (6) and (7) for each sector following IEC standard IEC 61400-12.

\[ U_{hub,j} = \frac{1}{N} \sum_{j=1}^{N} U_{hub}(T)_{j,k,j} \]  

(6)

\[ P_i = \frac{1}{N} \sum_{j=1}^{N} P(T)_{j,k,j} \]  

(7)

where:

- \( U_{hub,j} \) – normalized and averaged wind speed in bin \( i \)
- \( U_{hub}(T)_{j,k,j} \) – normalized wind speed of data set \( j \) in bin \( i \)
- \( P_i \) – normalized and averaged power output in bin \( i \)
- \( P(T)_{j,k,j} \) – normalized power output of data set \( j \) in bin \( i \)
- \( N_i \) – number of 10 min data sets in bin \( i \)

The met mast wind speeds at 10 m and 30 m at location M are used to determine the wind shear exponent \( a \) (8). Wind speed at 60 m are the estimated from the power law (9).

\[ \alpha = \log \frac{U_2}{U_1} \]  

(8)

where:

- \( U_1 \) – average wind speed at 10 m (m/s)
- \( U_2 \) – average wind speed at 30 m (m/s)
- \( z_1 = 10 \text{ m} \)
- \( z_2 = 30 \text{ m} \)

\[ U(T)_{30m} = U(T)_{10m} \left( \frac{60}{30} \right)^a \]  

(9)

A wind rose and EER are created for this location using the projected 60 m wind data and wind turbine power curve. This is compared to the wind turbine wind rose and EER at location WT for the same 7-month period, specifically from August 12th, 2019 to March 12th, 2021. This is specifically done to assess the impact of buildings in the south-west sectors as winds flow from location M to location WT over the 7-month period.

Directional annual wind power density (WPD) at multiple heights at the wind turbine site are determined from LiDAR measurements at location LiD. The WPD at higher heights of 120 m and 200 m are used to examine reductions and directional changes in WPD that may be introduced by the local building obstacles. The \( WPD_k \) in a given directional sector \( k \) (10) is weighted by the number of data points in that sector to give the directional \( WPD_k \) (11). The total \( WPD_{tot} \) is the summation of \( WPD_k \) over all sectors by (12).

The mean power density in a:

\[ WPD_k = \frac{1}{\sum_{j=1}^{N_j} \rho \, U(T)_{jk}} \]  

(10)

where:

- \( \rho \) – density of air (kg/m³)
- \( U(T) \) – 10-minute average horizontal wind speed at the height of interest

The time weighted WPD in a given direction is:

\[ WPD_k = WPD(T)_{jk} \frac{N_k}{N_{tot}} \]  

(11)
The total wind energy density is given by:

\[ WPD_{\text{tot}} = \sum_{k=1}^{N} WPD_k \] (12)

### 2.4. Turbulence and gust factors

Turbulence and gusts create dynamic fatigue and extreme static loads, than manifest themselves in turbine wear and failures. Equations for horizontal turbulence intensity \( I_u \) and vertical turbulence intensity \( I_v \) are described by (13) to (16).

\[ I_u(t, T) = \frac{\sigma_u(t, T)}{U(T)} \] (13)

The standard deviation is given by root mean square of the variance i.e.

\[ \sigma_u = \sqrt{w^2(t, T)} \] (14)

\[ I_v(t, T) = \frac{\sigma_v(t, T)}{U(T)} \] (15)

\[ \sigma_v = \sqrt{w^2(t, T)} \] (16)

where:
- \( u(t, T) \) - longitudinal fluctuation in wind speed
- \( w(t, T) \) - vertical fluctuation in wind speed

IEC 61400 design standards prescribe normal turbulence models (NTM), used in wind turbine design. NTMs are equations that give a longitudinal wind speed standard deviation relationship to horizontal wind speed, scaled by a reference turbulence intensity in the 15 m/s wind speed bin and other constant scaling factors. NTMs are given for both small scale and large scale wind turbines. In the case of large-scale wind turbines that conform to IEC 61400-1, a characteristic value of \( \sigma_u \) is given by (17).

\[ \sigma_u = I_{u,0}(0.75U(T) + b) \] (17)

where:
- \( I_{u,0} \) - reference turbulence intensity, specified as a fraction of \( \sigma_u \)
- \( b \) - constant = 5.6 m/s

\( I_{u,0} \) can have a range of values depending on the turbulence conditions at each height. Therefore, the predicted shear across the rotor disc is compared to power law (8) predicted shear across the lower and upper halves of the rotor disc using wind measurements at the lower blade tip height of 34 m, hub height of 60 m and maximum blade tip height of 86 m. The predicted shear profiles are extended down to 10 m and up to 120 m, a range of interest to distributed wind systems, to examine any deviations from the power law profiles from the measured shear profiles. Plots of the directional wind shear exponent \( a \) for both the lower and upper parts of the rotor disc are compared to test for any abrupt changes that might indicate building wake affects or internal boundary layer transitions across the rotor disc height range.

At locations with high wind shear or wind turbines with large rotors, the wind speed at hub height alone may not adequately represent the wind flow incident on the rotor. REWS attempts to account for variation

\[ \text{Fig. 5. Rotor segments and wind measurement heights used to calculate REWS.} \]
in wind speed across the rotor disc wind (Wagner et al., 2014), developed a method to calculate the REWS for large wind turbine rotors, from wind speed measurements at multiple heights across a rotor, for wind turbine with large rotors (e.g. rotor diameters above 90 m) in rural locations. Although the rotor of diameter of 52 m is relatively small in this case, the directional REWS is estimated from the LIDAR measurements across the rotor and compared to the hub-height wind speed.

\[
U_{\text{rews}}(T) = \left( \sum_{k=1}^{n_h} U_{k}(T) \frac{A_k}{A} \right)^{1/3}
\]

where:

- \( n_h \) = number of wind measurement heights
- \( U_k \) - wind speed measured at a given height within the rotor swept area
- \( A_k = g(z_{h+1}) - g(z_h) \) - is the area of the rotor segment between two heights \( z_h \) and \( z_{h+1} \)

\[
g(z) = (z - H) \sqrt{R^2 - (z - H)^2} + R^2 \tan^{-1}\left( \frac{z - H}{\sqrt{R^2 - (z - H)^2}} \right)
\]

\( R \) - rotor diameter (m)
\( H \) - hub height (m)
\( z \) - height of a point within the rotor span that is half way between two wind measurement points (m)

Fig. 5 shows a schematic of the rotor showing wind measurement for, at heights of 34 m, 60 m and 86 m and division into three segments at heights of 47 m and 73 m.

Turbulence also contains energy that can potentially be extracted depending on turbine rotor design. In terms of wind speed, the turbulent equivalent wind speed \( U_{h}(T) \) at each of the measurement heights can described by (21) (Wharton and Lundquist, 2012).

\[
U_{h}(T) = \sqrt{U_{h}(T) \left(1 + 3h_h \right)}
\]

\( U_{h}(T) \) at hub height is the specific case of \( U_{h}(T) \) when \( h \) is 2 i.e. the 60 m height and the REWS including turbulence is determined from (22).

\[
U_{\text{rews},h}(T) = \left( \sum_{k=1}^{n_h} U_{h,k}(T) \frac{A_k}{A} \right)^{1/3}
\]

A comparison of directional hub height wind speed \( U_{h}(T) \), rotor equivalent wind speed \( U_{\text{rews}}(T) \), hub height wind speed including turbulence \( U_{h,t}(T) \), hub height wind speed including turbulence \( U_{\text{rews},t}(T) \) are compared. This is done to assess if wind shear or turbulence has a bigger impact on wind speed deviation, across the rotor, from the hub-height wind speed.

3. Results

3.1. Obstacle morphological characteristics

For both M and WT locations, Fig. 6 shows obstacle weighted average height \( h_{\text{AW}} \) in the four 500 m segments for each of the 16 directional sectors. As expected, the morphological characteristics of the local

Fig. 6. Obstacle equivalent heights viewed from M at WT (top) and maximum obstacle heights (bottom).
obstacles are different when viewed from locations M and WT. However, the north and northeast sectors have similar values of $h_{AW}$ due to the spatial expanse of Dundalk town that consists of buildings of broadly uniform height and density. Differences in $h_{AW}$ occur in the remaining sectors from the southeast to the northwest, highlighting the differences between the rural and peri-urban locations in these directions. Specifically, at 157° for the WT location, the 47 m hotel primarily influences the value of $h_{AW}$ in the 0 m–500 m segment. In contrast, no obstacles are present for location M at 157°, in the 0 m–500 m segment, while the hotel appears in the 90° sector, in the 500 m–1000 m segment, that has a lower $h_{AW}$ value. The 202.5° sector location WT has a number of low-rise building from 11 m to 25 m in the 500 m–1500 m segments resulting in the highest instance of $h_{AW}$. This coincides with some of the lowest values in the corresponding segments for location M. In all westerly and northwesterly sectors, obstacles exist to some degree in all four segments for location WT. This is not the case for location M, where obstacles don’t appear in any 0 m–500 m segment and in some cases only appear in the furthest segment of 1500 m–2000 m, for example at 315°.

Fig. 7. Obstacle plan area fractions viewed from M at WT (top) and frontal area densities (bottom).

3.2. Long term directional energy assessment

At this site, the long term EER over 7 years, in Fig. 8 (top), shows that southwest and southeast directions are the most electrically productive sectors. Interestingly, consecutive energy peaks and troughs are observed in some neighbouring sectors from 90° to 270°. Lower energy values occur in sectors at 135°, 180° and 202.5° compared with higher energy values in sectors 112.5°, 157.5° and 247.5°. Selected directions that capture the best and worst case binned power curves show, that at wind speeds above 10 m/s, the best power curves occur at 90° and 112.5°, while poorer power curves appear at 157.5°, 202.5°, 225.5°, and 315°. However, plots of the directional power standard deviation and turbulence intensity, in Fig. 8 (bottom), clearly illustrate the direction nature of power performance and turbulence intensity.

The power curves with the highest variation occur in sectors 202.5° and 315° followed by 157°, 225° and 180°. In these directions, the
turbulence intensity values exceed the A+ level values of IEC NTM design values at wind speeds of 15 m/s for large-scale wind turbines and the NTM for small-scale wind turbines. The lowest variations in power curves occur at 90° and 112.5° and turbulence intensity values fall within both IEC NTM models. Table 2 qualitatively summarises the relative energy and turbulence in these sectors with respect to the obstacle morphological characteristics within each of their four segments.

The high turbulence and low energy of sectors of 315°, 202.5°, 225° and 180° have λP values of ~20% or higher in at least one of the first two segments up to 1000 m with hAW ranging from 6 m to 11 m. Sector 202.5° has a standout obstacle in its sector with a segment hmax of 25 m. The lowest turbulence sector and 112.5° have few obstacles in all segments denoted by lower λP values of 4%–13%. The hAW ranging from 8 m to 13 m. The 135° sector, with reduced energy, has higher values of λP from 25% to 59%. The turbulence is lower than the worst case 315° which may be due to the higher λP values occurring further away in the third and fourth segments. Sector 157° has values of λP from 15% to 31% occurring only in the third and fourth segments. Interestingly, it has higher turbulence than for sector 135°. However, it has the standout obstacle of the 47 m (hmax) high hotel within the first 0 m–500 m segment. The higher energy sectors of 247.5° and 270° have low λP values from 0% to 9%, but do not have the lowest turbulence. As the wind turbine rotor is well above the normal frontal view of the buildings, there are no obvious trends in the values of λP with energy or turbulence.

These initial finding suggest that λP values above 20%, in 16 sector divisions, combined with hAW values down to 10% of wind turbine hub height, within 1 km has an impact on turbulence and energy output. Standout obstacles of above ~1/3 of hub-height also have an impact regardless of λP value. However, they do not fully explain the higher turbulence in the 247.5° and 157° sectors that have low λP values.

Directional WPD plots based on one year of LiDAR measurement, at location LiD, from 34 m to 200 m are shown in Fig. 9. The WPD at the 200 m height shows winds from the Irish Sea specifically dominates the 157° sector, indicating a mesoscale influence from the coast. It reduces rapidly with decreasing heights below 120 m compared to its neighbouring sectors. This indicates high wind shear coinciding with the 47 m hotel i.e. wake effects of this single obstacle in a sector that otherwise has low λP values. This can also explain the higher turbulence in this sector. Low values of WPD appear at all levels in the 180° sector. This shows that local building are not wholly responsible for reduced energy in this sector, but rather, it is a low energy transition region between the higher southeast winds from the sea and the prevailing south-westerly winds.

The WPD in the southwest sectors from 202.5° to 247° sectors show the prevailing high energy sectors at 200 m. However, the energy in sectors 202.5° and 225° sectors is more reduced from 86 m and below, coinciding with the buildings in these sectors that have λP values in the first two sector of ~20%, in addition to a stand out 25 m obstacle occurs is in the 202.5° sector. These sectors are examined further with respect to the met mast measurements at location M.
### 3.3. Energy comparison between mast and wind turbine locations

An energy comparison is made between locations M and WT over the same 7-month period from August 2019 to March 2020. Firstly, the wind roses at 30 m at the mast location M and at the 60 m turbine hub-height at location WT, in Fig. 10, show that winds come mostly from the southwest during the assessment period. In the case of WT, wind occurrence in the 202.5° and 225° sectors are lower in comparison to sector 247.5°. At M, wind occurrence in the 225° are slightly higher than the 247.5° sector. It also has higher wind occurrences in sector 202.5° and lower occurrences in sector 270° compared to WT. This suggests local influence of the buildings to the southwest on wind flow. The northerly sectors at M have fewer obstacles, from Fig. 7, though winds at both were not frequent from the north of this test period. The southeast occurrences are also different at M, that also has a different obstacle morphology, but again in both cases, winds are low during the measurement to have a significant energy impact.

The impact on energy is illustrated using an EER overlay at hub height at M and the wind turbine location, shown Fig. 11a. Here, the met mast data at M projected to 60m using the power law (8) with measured data at 10 m and 30 m and combined with turbine power curve to produce the 60m EER at M. A directional shift in energy towards the west appears at the turbine location.

Table 3 shows the data values of Fig. 11b along with the direction energy differences between the wind turbine and met mast locations.

The directional energy values show that the biggest energy reductions at location WT are in the 202.5° and 225° sectors. When compared to the directional energy at location M, Fig. 11b, these appear to be compensated by energy enhancements in the 247.5° and 270° sectors. This suggests the low-rise buildings in the 202.5° and 225° sectors, λp above 20% in first two segments, are having a steering influence of the winds into the more open 247.5° and 270° sectors whose λp values are 20%. Low occurrences of wind and energy appear in the east to south sectors at both locations over the test period. However, the energy is distributed more evenly over these sectors in the case of M that has low λp values, well below 20%. The WT location has a better fetch to coast but small energy enhancements occur in sectors 112.5° and 157° with reductions in sectors 135° and 180°, which have λp above 20% in their first two segments. These find that if a sector is occupied by obstacles (λp>20%) and has neighbouring open sectors with fewer obstacles, then it is possible for energy to be shifted into the open sector(s) without a significant overall loss in energy. However, this may have implications for enhancing turbulence and wind gusts.

### 3.4. Turbulence intensity and gust factor comparison between mast and wind turbine locations

A comparison of the measured turbulence intensity at location M, at a 30 m height, with the WT location at hub-height is shown in Fig. 12 (top). Clearly, the turbulence intensity at location M is below IEC NTM levels and shows less directional variation when compared to location WT. The sectors with the higher turbulence at M are in the easterly sectors and lower in the south-westerly sectors. This can be explained by the presence of buildings to the east. As was observed in the long-term data analysis previously, the high turbulence at location WT occurs in the 202.5°, 225°, 247° and 315° sectors and approaches the limits of IEC NTM models. The turbulence intensity in the 90° and 112° sectors at location WT have the lowest values as they have the fewest obstacles in these sectors. Similar trends, Fig. 12 (bottom), are seen in the directional gust factor values with the value approaching 1.4 in the higher turbulence sectors. This suggests that energy shifted from the sectors with obstacles to neighbouring open sectors is accompanied by an increase in turbulence intensity and gust factors.

As turbulence intensity and gust factors are statistical and important parameters for extreme load calculations in the design of wind turbines, the mean binned values do not fully capture their potential ranges. For
Fig. 9. a) WPD at heights of 120 m and 200 m. b) WPD at heights of 34 m, 60 m and 86 m.

Fig. 10. a) 30 m wind rose at location M. b) 60 m wind rose at location WT.

Fig. 11. a) EER comparison at 60 m. b) Directional energy comparison.
information of interest to IEC wind turbine standard development regarding peri-urban environments, the 90th percentile of omnidirectional turbulence intensity at different heights are shown in Fig. 13a. The plots show that below a height of 60 m the IEC design standard values at 15 m/s are exceeded and would need to be at 86 m to meet current IEC recommendations. Typically, medium and large scale wind turbines have hub heights above 30 m while small scale turbines have heights up to 30 m. Therefore, suggested modifications to the IEC NTMs for low-rise peri-urban environments are plotted in Fig. 13b. The modifications to (17) is $I_{ref}$ of 0.2, and to (18) $I_{ref}$ of 0.25. These suggestions are for hub-heights from 2 to 6 times the value of $h_{AW}$ i.e. ~20 m–60 m, in this case. Below this height range the turbulence intensity appears excessive, while above it, the existing NTM models appear to be valid. However, further research is required in this area.

Vertical turbulence intensity is not currently considered in IEC standards. The mean binned directional vertical turbulence at 60 m for the LiDAR location shows a high range. It is observed to be approximately one third of horizontal turbulence intensity Fig. 14a. The directional trends are similar to the horizontal turbulence intensity. The 90th percentile gust factors are at 1.4 at 60 m and below, Fig. 14b.

These findings suggest that even though there may not be significant losses in energy due to energy being shifted from one sector to another, increases in turbulence intensity and gust factors may have implications for turbine wear and operational life. In particular at 60 m, below IEC NTM, predictions are exceeded and gust factors are high in this peri-urban environment.

3.5. Wind shear across the rotor and REWS

LiDAR measured wind shear profiles across the rotor disc, in the directional sectors of interest, are shown in Fig. 15. LiDAR measurements at 34 m and 60 m, which correspond to minimum blade tip height and

<table>
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<tr>
<th>Sector (°)</th>
<th>Met Mast M (kWh)</th>
<th>Wind turbine WT (kWh)</th>
<th>Difference (WT-M) (kWh)</th>
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<tr>
<td>0</td>
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<td>31518</td>
<td>1442</td>
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<td>5905</td>
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<tr>
<td>Total</td>
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<td>1076473</td>
<td>58902</td>
</tr>
</tbody>
</table>

Table 3
Directional energy comparison over 7 months.

Fig. 12. Directional turbulence intensity at M and WT (top) Directional gust factors at M and WT (bottom).
hub height respectively, are used as input to the power law (8) to
downscale and upscale the horizontal wind speed over the 10 m–120 m
height range. Similarly, LiDAR measurements at 60 m and 86 m, which
correspond to hub height and maximum blade tip height respectively, are
used to downscale and upscale wind speed over the same height range.
The resulting scaled profiles are plotted alongside the actual measured
LiDAR profiles from 10 m to 120 m to assess deviations between the real
and scaled profiles.

The best fits across the rotor occur for sectors 225°/C14, 247.5°/C14
and 270°/C14 suggesting the wind flow is in steady state as described by the power law.
The extended power law profiles deviate the least from measurements. In the cases of 180°, 202.5° and 315° deviations occur within the rotor disc.
Upscaling of winds from the bottom half of the rotor under predict winds
in the top half of rotor and above, while downscaling winds from the top
half of the rotor under predict winds in the bottom half of the rotor and
lower down. This suggests winds measured at lower levels, below hub
height, in these sectors have a higher proportion of data points with
higher wind speed values. In other words, the building obstacles have a
lower impact on incoming winds of higher wind speed. This may explain
why the neighbouring open sectors of 225° and 247.5° has slightly over
predicted winds due to the steering wind of lower wind speeds less than
~5.5 m/s into these sectors. The deviations are most evident in sector 315°, that has λ_P values from 24% to 57% with h_AW of 6 m–7 m. These
deviations suggest that sectors λ_P values above 20% impacts wind flow at
the rotor disc level. These results show that it would be unrealistic to
increase the hub height to the extent to have the rotor fully above the
influence of the low-rise buildings. The worst-case deviation occurs in the
high energy sector of 157.5°, which lies in the wake of the tall narrow 47
m building. In the case of the 90° sector, which has few obstacles, the
lowest wind shear exponent occurs in the upper half of the rotor disc and
the shear of the measured profile reduces fastest above the rotor. This
may also be influenced by atmospheric instability in this sector, due to
coastal influence, particularly in the spring and summer seasons when
onshore sea breezes are more common. This is also seen to a lesser extent
in sector 157.5°.

Fig. 16a shows the difference in shear exponent between the bottom
and top halves of the rotor, evident from 157.5° to 225° and from 292.5°
to 0° (360°) which coincide with buildings. The larger variation in sector

Fig. 13. a) 90th percentile turbulence intensity at various heights b) Suggested modification to IEC MTMs.

Fig. 14. a) Directional vertical turbulence intensity at 60 m b) Omnidirectional 90th percentile gust factors.
Fig. 15. a) Fitted power law profiles to LiDAR measured directional wind profiles across the rotor disc WTR.
315° coincides with the higher $\lambda_P$ values. The deviation between 112° to 135° occurs as the LiDAR measurements are in the rotor wake. The directional REWS considering shear and turbulence, separately and combined, are compared with the hub height wind speed in Fig. 16b. Turbulence has more of an influence, giving an additional effective wind speed of up to 0.25 m/s. In the case of 157.5° that has the highest shear, there is an equal influence with turbulence giving a combined influence of 0.5 m/s. Therefore, unlike for larger wind turbines in rural environments where wind shear across the rotor is considered important, wind turbulence appears to be more important for medium and large wind turbines in peri-urban environments.

4. Discussion

This study shows that existing obstacle rules used in wind turbine micro-siting, based only on obstacle height and distance, may not be sufficient for peri-urban environments. It is observed that low-rise buildings with heights greater than 20% of hub height can influence wind turbine performance. The influences are complex depending on the layout the buildings, areas occupied and distances from wind turbine location. A multi-sectoral morphological approach to assessing the collective impact of multiple obstacles can provide a simplified means to micro-siting single medium and large-scale wind turbines in peri-urban environments. Where the rural to urban transition occurs within 1 km of a wind turbine’s location, a 16-directional sector division of the area surrounding the turbine, shows that in a given sector, obstacles with a $h_{AW}$ of 20% of the turbine hub height and a $\lambda_P$ higher than 20% have an energy reducing affect. However, it is also found that if a neighbouring sector is relatively open, to the rural environment, with plan area fraction of less than 10%, the energy can be recovered by the steering of winds around the blocked sector into the more open sector. The steering of winds appears to be more prevalent at wind speeds below ~5.5 m/s, while higher wind speeds are less affected. This is relevant for peri-urban sites that may have lower annual average wind speeds in general. Therefore, for a 16 directional sector analysis within a 1 km radius, it is suggested that a wind turbine should be sited in the prevailing wind sectors such that $\lambda_P$ less than 20% in these sectors, when viewed from the wind turbine location. If $\lambda_P$ is above 20%, then the minimum height of the bottom of the rotor disc should be at least four times $h_{AW}$ of the sectors. In addition, any obstacle with a maximum height above 1/3 of the turbine hub height (or 50% of the height of the bottom of the rotor disc), in the prevailing wind sectors, should be avoided, particularly within 500 m. In the case of small wind tower mounted turbines, these criteria should be met for their typical hub heights of up to 30 m.

Higher wind turbulence and gust factors are observed to increase significantly compared to the rural location upwind of the obstacle influences. The 90th percentile turbulence intensity values at the wind turbine location exceed limits of current NTM in current IEC standards below heights of 86 m, in this case, with high exceedance below 30 m. This suggests a need to revise current IEC standards for medium and large wind turbines deployed in peri-urban environments. With reference to the IEC NTM for large wind turbines described by (17), suggested modifications of “$I_{ref}$” to “0.2” would better account for turbulence for turbines with a hub height from 30 m up to 6 times the value of $h_{AW}$. At heights above this, the existing NTM for large scale wind turbines appear valid. For small wind turbines on shorter towers, NTM described by (18), suggested modifications of “$I_{ref}$” to “0.25” would account for turbulence intensity down to 20 m i.e. approximately twice the height of the majority of surrounding buildings. The implications of these findings are that wind turbine designs may need to be more robust for peri-urban wind environments and to meet any new IEC revisions that may be made in the future. Gust factors exceed the current small wind design standard values of 1.4 below 60 m, which are more of a concern for small wind turbines. The power law best fits measured wind shear across the 52 m rotor diameter in open sectors with $\lambda_P$ below 10%. Its deviation increases with increasing plan area fractions above 20%. For standout obstacles, the biggest deviation occurs in a sector that contains a 47 m obstacle 330 m away from the wind turbine. REWS, accounting for both wind shear and turbulence, exceeds hub-height wind speed from 0.25 m/s to 0.5 m/s. It is shown to be dominated by turbulence in all sectors apart from the sector in the wake of the 47 m obstacle. However, it shows that it may not be a critical parameter to assess for rotors of this size.

Overall, the learnings from this study can be of benefit for low cost pre-feasibility assessments for medium and large-scale turbine deployed in peri-urban environments. Current wind micro-siting tools with linear obstacle/shelter models that treat wake effects of single obstacle elements can be difficult to implement in environments with many obstacles. These tools could be further enhanced using morphological methods to help capture bulk effects of multiple obstacles on the wind resource. The study also shows the usefulness of LiDAR technology in the assessing the wind resource in peri-urban environments, in terms of ease of deployment, detailed wind measurements at multiple levels applicable to both large and small-scale tower mounted wind turbines.

5. Conclusions

Careful considerations are required when micro-siting single wind turbines, with respect to surrounding buildings, in peri-urban environ-
ments. A 16-directional sector analysis shows that, sectors with obstacle plan area fractions above 20%, within 1 km of a wind turbine’s location, can have an energy reducing impact if the average, plan area weighted, obstacle height is above ~20% of the wind turbine hub height. However, the energy can be recovered, by the steering of winds, in cases where a sector with a high obstacle plan area fraction has a neighbouring sector with an obstacle plan area fraction below 10%. It may not be practical to increase a wind turbine’s hub height to a height above the influence of buildings; therefore, the rotor may always be in complex flow to some extent. However, it is suggested that within a 1 km radius of a wind turbine’s proposed location, it should be sited in the prevailing wind sectors such that the obstacle plan area fractions are less than 20%. If they are above 20%, then the height of bottom of the rotor disc should be at least four times the average, plan area weighted, obstacle height of the sectors. In addition, any obstacle with a maximum height above 1/3 of the turbine hub height (or 50% of the height of the bottom of the rotor disc), in the prevailing wind sectors, should be avoided, particularly within 500 m. It is also suggested that IEC wind turbine standards be revised in relation to normal turbulence models for peri-urban environments. The 90th percentile values of turbulence intensity have been shown to exceeded at heights below 6 times the average, plan area weighted, obstacle height. Modification of “{$I_{p}$}” to “0.2” for large-scale wind turbines and “0.25” for small-scale wind turbine are suggested for peri-urban environments. Future research in distributed wind should include the optimising the deployment of medium and large-scale wind turbines in peri-urban environments. It is expected that LiDAR technology will become a more prevalent and necessary tool in the distributed wind industry in the future as its cost reduces.

CRediT authorship contribution statement

Raymond Byrne: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. Neil J. Hewitt: Supervision, Project administration, Writing – review & editing. Philip Griffths: Supervision, Writing – review & editing. Paul MacArtain: Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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