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Urban Deployment of Small Wind Turbines: Power, Performance and Turbulence

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Abstract- **The urban terrain and the associated topographical complexities therein, present significant challenges to the deployment of small wind turbines. In particular, a considerable amount of uncertainty is attributable to the lack of understanding concerning how turbulence within urban environments affects turbine productivity. This paper considers how the industry standard metric, turbulence intensity (TI), in conjunction with the power characteristic of a 2.5kW wind turbine, can be employed to estimate turbine power performance. The research presented here considers the potential productivity of a wind turbine installation at two sites in (urban and suburban) Dublin, Ireland where the prevalent turbulence at both locations is considered. The industry metric of TI and the statistical properties of the high resolution wind observations at both locations are utilised to drive two models. The high resolution nature of the wind speed observations facilitates accurate application of Gaussian and Weibull statistics in this regard. The analysis demonstrates that the proposed methodologies could provide a means for installers to accurately predict power performance for a wind turbine based on (wind speed) standard deviation and TI observations.**

Index Terms **-- Small wind turbines, urban environments, turbulence, turbulence intensity, Gaussian and Weibull distributions**

I. INTRODUCTION

There are many challenges to incorporating wind generation into urban areas. From a wind resource perspective, these environments are characterised as being very rough and heterogeneous and turbines installed in these locations will experience site-specific, localised turbulence. Research into this topic demonstrates the significance of turbine position and mounting height *vis-a-vis* buildings or other adjacent objects, such that small changes in location can have dramatic effects on the power generated [1-3]. Furthermore, studies indicate that turbines installed in urban environments, being subject to turbulence appear to underperform when compared to installations in non-turbulent environments [4, 5]. In contrast, research assessing the wind energy resource in 'rural' locations points to the relative amenability presented by such sites to the facilitation of wind energy systems [6, 7]. However, notwithstanding the issues which urban environments present, if a renewable solution to increasing energy demand is to be achieved, wind energy - especially where civil populations are increasingly concentrated - must be explored.

Two models are considered. The first approach is an adaptation of a model originally developed to quantify the degradation of power performance of a wind turbine using the Gaussian distribution to simulate TI [8]. This approach employs the observed TI in conjunction with the power characteristic of a 2.5kW wind turbine to predict the power productivity of the wind turbine. The second model, a further development of the Gaussian approach, employs the Weibull distribution, so that turbine power prediction, independent of the associated power characteristic is achievable. Both models are tested at an urban and suburban location in Dublin, Ireland. Sonic anemometry is positioned, cognisant of installation location surface characteristics, to record the three dimensional wind vectors at a temporal resolution of 10Hz. These models are then subsequently benchmarked against the industry methodology of using average wind speed over a wind speed observation window to calculate the associated turbine power

II. SMALL WIND ENERGY SYSTEMS: AN URBAN CONTEXT

Urban wind regimes are characterised as having low wind speeds with more turbulent flow that results in limited energy realisation. Air flowing across an urban area will interact with the underlying urban subtype and become affected by its characteristics. The net effect is that a series of Internal Boundary Layers (IBL) form in the along-wind direction. The dominant process in the lower atmosphere is convection. The type of convective activity, is influenced by the vertical temperature structure and is expressed by stability or the relative tendency for an air parcel to move vertically [9]. There are three classifications used: unstable, stable and neutral but due to the enhanced mixing experienced in urban areas results, the urban boundary layer is generally in a neutral state. Research carried out by Metzger and McKeon [10] demonstrates that in neutrally stable environments, surface roughness dominates turbulence production. The authors suggest that the effects of buoyancy and thermal parameters are wholly negligible when considering wind flow and turbulence and so wind speeds are dependent on the mechanical effects of surface roughness. Within rural

environments, the log wind profile (1) is commonly employed as a means of estimating the wind resource

$$u(z) = \frac{u_*}{\kappa} . \ln\left(\frac{z - z_d}{z_0} \right) \qquad (1)$$

where k is von Karman's constant (0.4), z is height above the ground, z_o is the roughness length and z_d is the displacement height and z* is the wake diffusion height. The friction velocity (u_*) is a measure of the shearing stress that drives the flux of momentum to the Earth's surface. This relationship describes wind-speed in the direction of airflow within a boundary layer where airflow has adjusted to the underlying surface. It is properly applied to extensive homogeneous surfaces (such as grass) under neutral atmospheric conditions and is valid under these circumstances to heights (z) above (z_d+z_o), where z_o the displacement height identifies the level of the aerodynamic surface where u(z) (obtained from (1)) goes to zero.
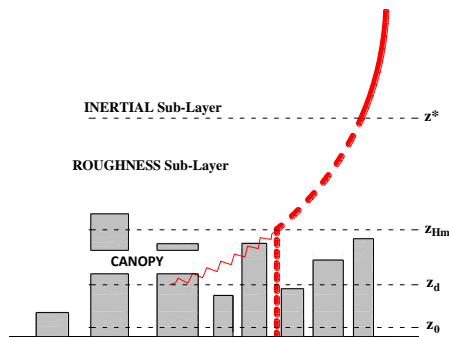

Fig. 1: Urban Air-flow model in terms of the logarithmic model (1). This profile performs well above z*, but within the roughness sub-layer (z*<z>z_{Hm}) the associated wind is dominated by turbulent eddies making wind classification less reliable.

In urban environments, a distinct roughness sub-layer between the mean building height (z_{Hm}) and the wake diffusion height (z*) is created and within the roughness surface layer (RSL), the logarithmic profile (1) is no longer applicable. From a wind resource perspective topography, the building morphology and the roughness length of the urban surface, z_0, are the significant parameters to be considered when assessing the turbulent structure of air masses [10-12]. The factitious nature of the urban topography is discussed by Fernando in [13] and fluid dynamic analyses performed in [14] describes the complexity associated with the urban topography as being the rule governing the wind resource. Indeed, this work further describes how the flow through urban canopies is highly sensitive to building morphology.

Turbulent flows can be described as those in which the fluid velocity varies significantly and irregularly in both position and time [15]. While turbulently fluctuating flow impacts directly on the design of wind turbines, they also influence the productivity of power within the turbines – particularly in areas of complex morphologies. Turbulence Intensity (TI) is the most common metric to explain the turbulent effect as it is generally more useful to develop descriptions of turbulence in terms of statistical properties [16]. The design requirements for small wind turbines in urban environments are defined by IEC 61400-2 [17]. TI is defined in [17] as "the ratio of wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified time" and should actually be considered as the standard deviation of the wind speed σ_u normalised with the mean wind speed $\bar{u}$ (3).

$$TI = \frac{\sigma_u}{\bar{u}} \qquad (3)$$

It is generally accepted that with respect to turbulence, there are two components (gusting and change of direction) that affect the performance of micro wind turbines. The gusting component is currently classified by means of the longitudinal turbulence intensity as described in [17, 18]. In ascertaining the impact of the longitudinal turbulence intensity, the cosine-corrected longitudinal wind speed, the normalised observed wind speed along the mean wind direction, is employed.

With respect to the impact on the power output of wind turbines subjected to turbulence, the majority of the available research considers utility scale systems with capacities in the MW ranges [19-22]. Cochran, [23], considered empirically linking surface roughness and the power law wind shear coefficient to turbulence manifestation. He further presented a description for turbulence intensity within the lower portion of atmospheric boundary layer also based on surface roughness. His conclusions were that the (kinetic) energy available at the turbine hub height can vary by as much as 20% depending on the level of TI present at a site. In [20-22], the effect turbulence intensity has on the power curve of a turbine is that high TI exaggerates the potential output power from a turbine at moderate wind speeds, whereas low TI undermines the potential output power at rated wind speed.

III. METHODOLOGY

The following sections detail how both models are developed in the MATLAB7^{TM} programming environment.

A. Wind Observations & Context

There two observation sites used in this research representing two distinct urban landscapes with Dublin City, Ireland. One is located close to the city centre (URB1) in an area that has mixed residential, industrial and commercial uses. The buildings vary considerably in dimensions and there is comparatively little green space. The other is located in a mature, vegetated suburb (SUB1), where the dimensions of the buildings are nearly uniform and the land use is residential in character. At each site the observation platform is at least 1.5 times the average height of buildings and both platform locations are cognisant of the prevailing surface roughness characteristics within both environments. Each of the stations is positioned within a broadly defined

'homogenous' landscape in the sense that the character of the surrounding urban morphology is similar in all directions. This is especially true of the suburban site.

At both sites, high-resolution wind speed measurements are taken with a *Campbell Scientific* CSAT3 three-dimensional sonic anemometer. The observations are at 10Hz at an associated resolution-between 0.5 and 1.0 mm/s, with data that includes date and time-stamp, wind-speed, wind-direction and standard deviation. The CSAT3 measures wind speed employing a right handed orthogonal coordinate system. Three orthogonal wind components, which relate to the three dimensions in space, are each measured. Wind entering straight into the anemometer is from the +x direction, u (effectively the northerly component); wind approaching from the left of the anemometer is from the +y direction, v (the easterly component); and wind advancing upwards from the ground is from the +z direction, w. Measurements are taken over a 40 day period from 4/4/2012 to 15/5/2012. Consistent with [17], a 10 minute sampling period bench mark, this period is used on a moving window basis, each window consisting of 6000 samples (10 minutes at 10Hz).

B. Modelling

1) Albers Approximation

The methodology is predicated on utilising the wind turbine power characteristic in terms of a 'look-up table' that defines the power generated for a given TI and wind speed, i.e., for an observed mean wind speed and TI over an observation window, a normalised turbine power output can be referenced. In the context of both methodologies being proposed in this paper, the turbine characteristic is ideal and considered as being derived without any influence of a turbulent environment. The characteristic employed was acquired from HOMER^{TM} (Hybrid Optimisation Model for Electric Renewables (version 2.81) as developed by the US National Renewable Energy Laboratory (NREL) [24]. The specific turbine characteristic (Skystream 3.7, 2.5kW) is decomposed within MATLAB into a polynomial equation which can be applied to any set or subset of wind speeds subject to:

$$P_{Turbine}(u)\begin{vmatrix} P_{(1.5<u<25)m/s} = P_{(Characteristic)} \\ P_{(25<u<35)m/s} = P_{(25m/s)} \end{vmatrix}$$

with both conditions dependent on the normalised TI Fig. 3 illustrates how the *Skystream 3.7* characteristic is applied in the analyses (both models)

The Albers approach, which quantifies the degradation of power performance of a wind turbine [8] is modified so as to predict the power performance based on raw wind resource observations. Employing an approximation to the Albers' approach, the turbine characteristic can be normalised to any level of TI.

Albers' approach [8] involves normalising the wind turbine power curve based on measurements. His approach considers the zero turbulence power curve with respect to the normal distribution model as utilised in [17]. More specifically, in [8], the wind turbine power can be simulated by considering

the variation of wind speed within a window of measurement (10 minutes and 6000 wind speed datums/window (10Hz)) as following a Gaussian distribution in terms of:

$$\overline{P_{sim}(u)} = \int_{u=0}^{\infty} P_{I=0}(u).f(u)dv \qquad (4)$$

where f(u), is the wind speed distribution within the 10-minute period (Gaussian wind speeds, normally distributed about the mean), $P_{I=o}(u)$, is the zero turbulence power curve and $\overline{P_{sim}(u)}$ is the simulated 10-minute average of measured power output
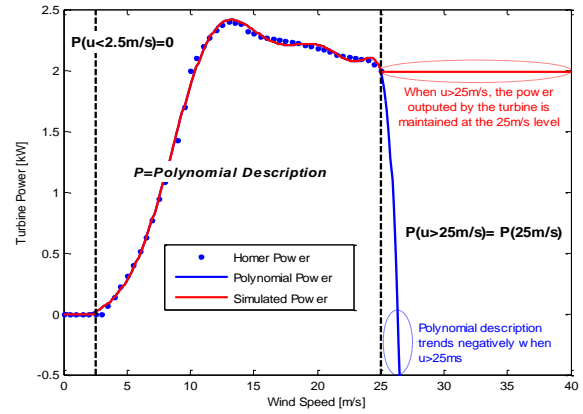

Fig. 3: Illustrates the modification of the Skystream 2.5kW Wind Turbine Power Characteristic as both modelled and then utilised in analyses.

The basis of Albers' approach applied here for a micro wind turbine is with respect to (8) and is summarized in fig. 4.

$$\overline{P_{Norm}(u)} = \overline{P(u)} - \overline{P_{sim}(u)} + \overline{P_{ref}(u)} \qquad (5)$$

where $\overline{P(u)}$ is the ten minute average of measured power output, $\overline{P_{sim.I}(u)}$ is the simulated 10-minute average of measured power output according to (4) applied in terms of the measured wind speed distribution and assumed TI (nominally, 10%). The standard deviation of the turbulent wind at an assumed TI and measured mean wind speed over the observation window, is accounted for in $\sigma = TI_{sim} \times u_{mean}$. $\overline{P_{sim.}(u)}$ is the simulated 10-minute average of measured power output according to (4) applied for the measured wind speed distribution (i.e. measured average wind speed and measured TI over the 10-minute window) by assuming a Gaussian wind speed distribution.
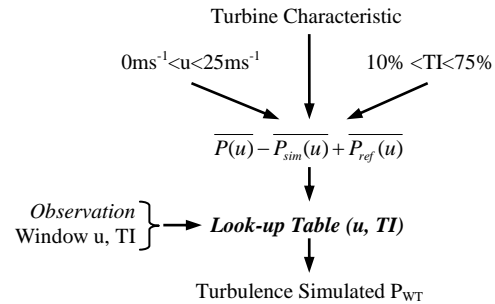

Fig. 4: Flow Chart describing the *Albers Approximation* as utilised to derive the normalised turbine output in a turbulent environment. The methodology collates the output of a wind turbine output based on its idealised characteristic, its range of operational wind speeds along with a range of practicable TI levels, into a 'look-up table'.

2) Weibull Approximation

The Weibull normalized power is calculated by implementing a normalized PDF that meets the same sample criteria for mean wind speed and TI, as that measured over the observation window. An average power value is calculated based on 6000 artificially generated data points and the modelled Weibull PDF(s) in terms of the specific turbine characteristic (Skystream 3.7). Unlike the Albers approximation, the Weibull approximation has two stages, which are summarised in Fig. 5, which presents a flow diagram of the model. Multiple Weibull PDFs are created by varying shape and scale parameters. The shape factor is varied from 0.05 to 30 in 0.01 increments in conjunction with varying scale factors, from 0.05 to 15 in 0.01 increments (c4.6 million PDFs). These PDFs are subsequently interrogated against practical wind speed and TI references, i.e. the best fit for reference in a look-up table, as per the Albers approximation. Closest fit between the desired wind speed/TI parameterisation is acquired through error detection.
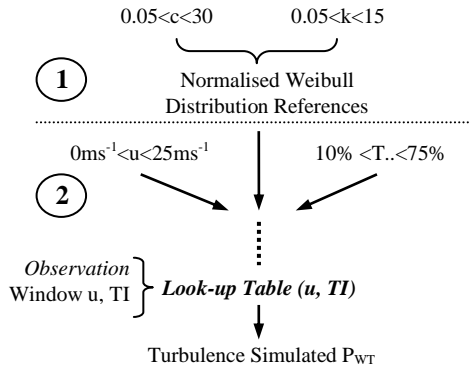

Fig. 5: Flow Chart describing the *Weibull Approximation* as utilised to derive the normalised turbine output in a turbulent environment.

IV. ANALYSIS

Over a 40 day period from 4/4/2012 to 15/5/2012, 10Hz measurements are organised into 10 minute observation windows. Each observation window considers three power measurements: the *Albers approximation* P_{norm}, the *Weibull approximation*, P_{weib} and the average power over the window, P_{mean}, which is calculated by considering the turbine characteristic with respect to the mean speed over the observation window. P_{mean}, is the industry norm for data logging of power output from wind turbines. Each of these calculations are benchmarked against the *absolute power*, P_{abs}, which is the average of individualised (6000) calculations of power over the observation window and represents the truest measure of generated power by the turbine. Fig. 6 illustrates scattergram comparisons of the three turbine output power measurements (P_{mean}, P_{norm} and P_{weib}) with respect to P_{abs} at URB1, (A) and SUB1, (B), respectively. An ideal comparison for either of the three calculation methodologies would give a 1:1 slope ratio (m=1) with an associated intersection and correlation of 0 and 1 respectively. This comparison shows that there is a strong correlation between the Albers (P_{norm}) and Weibull (P_{weib}) approximations to the absolute power generated over the observation window (P_{abs}).

The average power (P_{mean}) at both locations is shown in general, to underestimate at lower wind speeds, whereas at higher wind speeds, there is a potential to overestimate.
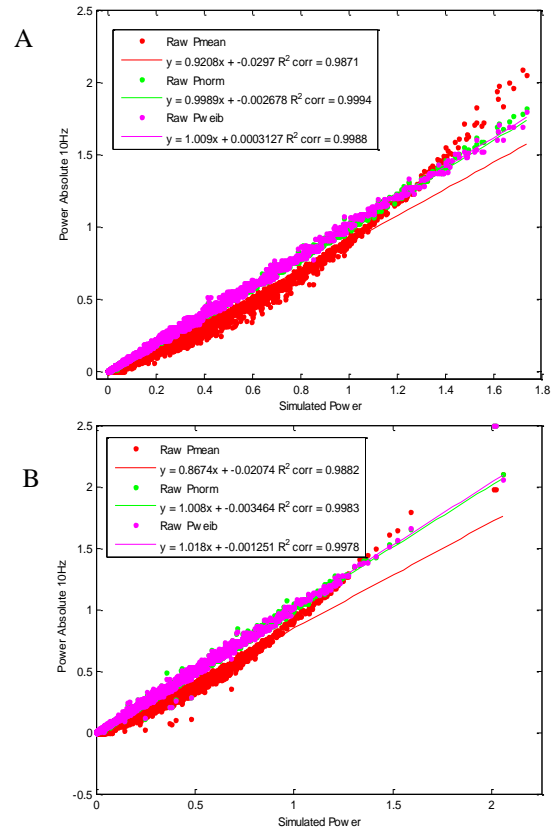

Fig 6: Scattergram comparisons of P_{mean}, P_{norm} and P_{weib} with respect to P_{abs}. For both URB1 (A) and SUB1 (B). There is evidence of strong correlation with P_{norm} and P_{weib}, whereas P_{mean} is seen to under predict overall with respect to P_{abs}.

The comparison presented in Fig. 6 is further considered to establish if there is an underlying trend in the power prediction methodologies and whether the simulated models under or overprescribe with respect to P_{abs}. Fig. 7 presents a cumulative sum of differences that occur throughout the full set of 40 days for URB1, but the same consideration for SUB1 produces a similar trend, in that, P_{weib} and P_{norm} are virtually horizontal, with only a slight over prediction derived using P_{weib} and under-prediction using P_{norm} cumulatively derived over the 40 days of observations.
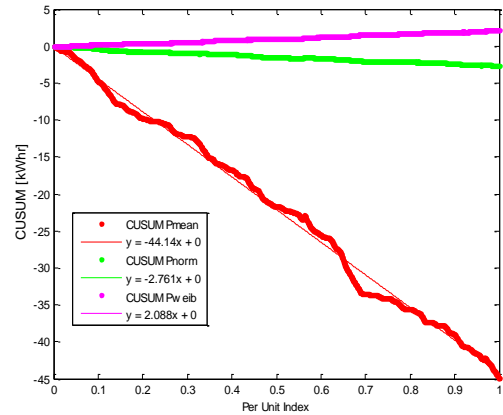

Fig. 7: The cumulative error for each of the calculated power models (P_{mean}, P_{norm} and P_{weib}) for URB1. While there is some over estimation of output power in URB1 with some underestimation evident at SUB1 in terms of the P_{weib} model, in context with the other models, this inaccuracy is negligible

If the cumulative error characteristic is considered, the probability of an error being below a given kW rating for a given simulated model, Fig. 8 illustrates (for SUB1) that the P_{weib} model has over 90% of its error within 50W of the P_{abs}. This is consistent for both sites.
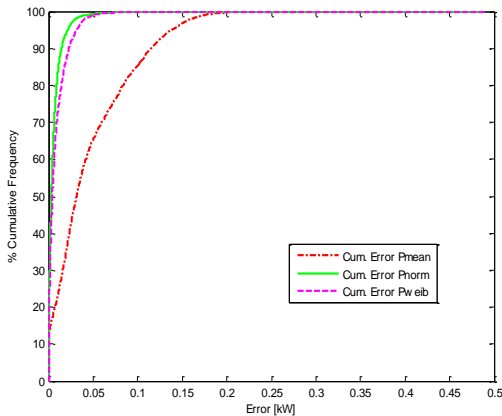

Fig. 8: The cumulative error characteristic for the power prediction models at SUB1, illustrating the accuracy of the Weibull approximation.

Finally, the mean absolute error (MAE) between the power estimation models and the absolute power estimated over the observation window is considered. Fig. 9 illustrates the MAE for SUB1 in terms of binned wind speeds. Similar results were observed for URB1. There are significant and consistent errors derived with respect to P_{mean}, whereas the P_{norn} and P_{weib} models perform reasonably well across the spectrum of wind speeds, albeit with a tendency to introduce error (<75W) at high wind speeds .
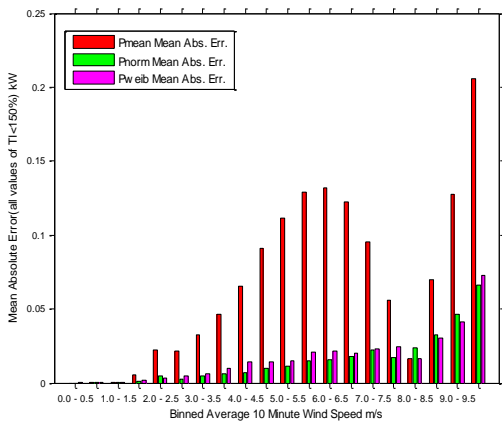

Fig. 9: MAE (SUB1) of the power estimation methodologies with respect to P_{abs}. The illustration suggests an increased likelihood of error potential with the Albers approximation at low wind speeds, whereas, there is an increased potential for error at increased wind speeds with the Weibiull approximation.

This analysis shows that Gaussian and Weibull probabilistic statistics, considered in terms of TI observations, can provide an accurate means to estimate the power output of a wind turbine at both a suburban and urban location. Is there a way therefore, to characterise T.I in terms of surface characteristics across all types of urban location? Grimmond and Oke in their work pertaining to the aerodynamic properties of urban areas, [25], summarise first order estimates of d and z_0 (displacement height and surface roughness length respectively) for the urban context.

According to this classification [25] and with respect to the two locations in Dublin, SUB1 is characterised as 'Low Height and Density', whereas, URB1 is characterised as 'Medium Height and Density' and both sites have distinctive and different surface roughness lengths. The ultimate aspiration would be a means to provide TI boundaries for any wind speed in terms of surface roughness, which requires an ability to trend TI across the spectrum of practical wind speeds. An obvious way to consider this is with respect to average TI in wind speed bins, as illustrated in Fig. 10
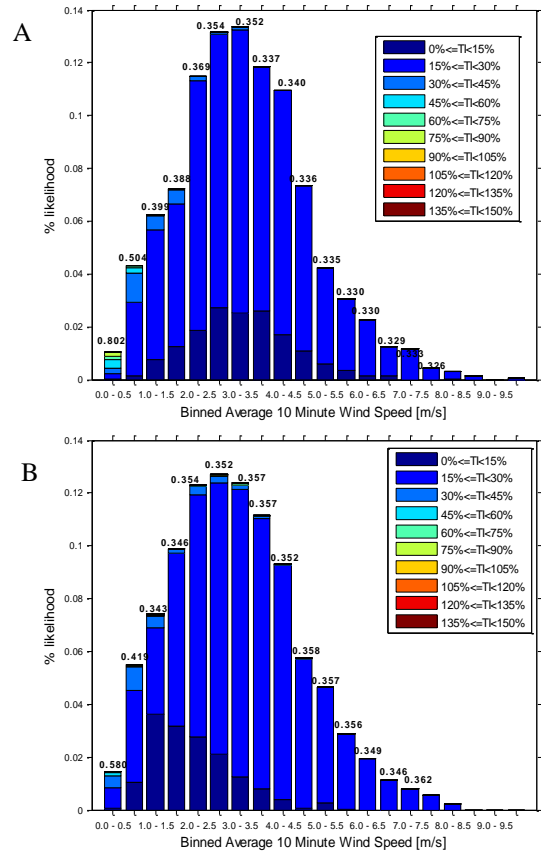

Fig. 10: Binned TI (15% bins) with respect to binned wind speed (0.5m/s bins) representing observations at URB1 (A) and SUB1 (B). TI is filtered so that only TI<150% are considered. Average TI per wind speed bin is also superimposed.

Fig. 10 illustrates wind speed distribution inconsistency at both sites. This will bias the average TI so that above 3m/s, so that the average TI observed at SUB1 will appear to be greater than observed at URB1, contrary to an intuitive expectation that at sites with increased surface roughness lengths, TI will be higher. Also, the number of observations at both sites within each wind speed bin will introduce biasing of TI averaging. Furthermore, the proliferation of unrealistically high TI at low wind speeds (0-1m/s) will contribute to this biasing effect. These abnormalities have the effect to skew the average TI. If one speculates however, with respect to the lower wind speeds, where TI and turbulence has the most effect and where biasing within the 40 days of observations has less effect, there is scope for speculative trending. Fig. 11 illustrates a speculative trend, cognisant of the different surface roughness characteristics describing both URB1 and SUB1 respectively.

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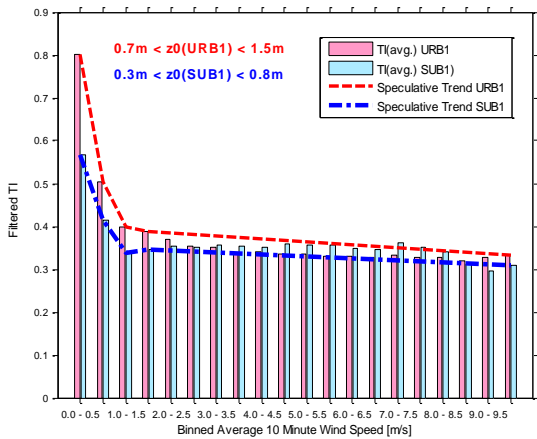

Fig. 11: Average TI in terms of binned wind speeds at both urban locations (SUB1 and URB1). The TI bins are filtered so that only TI<150% are considered. Trend lines are included as speculative reference.

V.   CONCLUSIONS

Two mathematical models have been proposed. The first, an adaptation of Albers' work [8], and the second, employs an alternative to the Albers' Gaussian statistics approach to derive indicative TI by using the Weibull distribution. The structure of both models is similar with the exception that the Weibull approximation does not require the wind turbine characteristic, whereas the Albers approximation is based on knowledge of an accurate power characteristic. Both models were benchmarked using the Skystream 3.7 (2.5kW) wind turbine, which is representative of commercially available technologies in similar ranges.

The results confirm that both models are consistent with P_{abs} with over 90% of all simulated powers are within 50W of the P_{abs}, implying 90% of readings are within 0.2% error. The Albers' approximation tends to over-predict (slightly) with the opposite outcome when using the Weibull approximation. The industry norm for evaluating power, however, significantly under-estimates at lower wind speeds and over estimates considerably at higher wind speeds. Both models also introduce errors with increasing wind speed, but in comparison to the industry norm, these errors are negligible

In an energy context, the errors derived by the industry standard approach, results in an under-estimation of 24.2% and 20.5% at SUB1 and URB1 respectively (Fig. 7).

However, there are issues associated with TI as a metric for turbulence. TI does not facilitate chronological and time-indexed trending of the wind speed observations, where inter-variability of wind speed perpetuates turbulence. There is also a potential for unrealistic levels of TI within observations owing to gusting and occurrences of very low wind speeds. The latter effect significantly impacts on the practicality of the average TI as a metric, particularly if it can be employed as a means to link a description of the urban environment (z_0) and average wind speed to propose how the power output of a wind turbine is effected (Fig. 10).

ACKNOWLEDGEMENTS

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