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To cite this article: A KC et al 2018 J. Phys.: Conf. Ser. 1037 072022

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A comparative analysis of built environment and open terrain wind data by higher order statistics and performance evaluation of 5 kW HAWT using FAST

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Abstract. Small wind turbines (SWT) that are designed as per the IEC 61400-2 standard suffer structural and operational complexities when operating in the built environment, because such environments impose stochastic variations in wind speed and turbulence. The wind conditions in flat terrain of Östergarnsholm (OG) Island, Sweden and built environment of Port Kennedy (PK), Australia are compared for turbulence intensity (TI) and intermittency. The TI of the PK wind field was 24% at mean wind speed of 15 m/s, which was higher than the Normal Turbulence Model (NTM) indicated in IEC 61400-2. The TI in the open terrain was below 18% for all mean wind speeds. Similarly, for three chosen wind speed bins within a SWT’s operating range, the urban wind field had higher intermittency for smaller timescales but resulted in smaller intermittency as the time lag increased. The effect of these measured wind fields on the performance and loading of a turbine was studied at the three chosen wind speed bins using an aeroelastic model of a 5 kW SWT that was developed in FAST. The predicted output statistics using measured wind fields were compared with the assumed wind fields in the IEC 61400-2 standard. The rotor thrust and blade flapwise bending moment with PK wind data were higher than that of the IEC standard due to the increased turbulence in the inflowing wind indicating the inadequacy in the current wind standard applied for such SWTs for urban installations.

1. Introduction

Small wind turbines (SWT) are designed based on the International Electrotechnical Commission (IEC) 61400-2: Design requirements for small wind turbines [1]. According to the standard, the SWTs have a swept area less than 200 m², corresponding to a rotor diameter of less than 16 m. The standard incorporates the stochastic turbulent wind models, which are used as an input into the aeroelastic codes to simulate the flow fields, calculate design loads and predict the structural loading on SWTs. These models are based on observations taken in open terrain and do not suitably reflect the built environment (urban or suburban) wind conditions, which are characterized by lower wind speeds and higher level of turbulence due to higher roughness level, presence of obstacles and their interactions with the incoming wind profile [2]. SWTs are generally incorporated within the built environment as building-mounted on the side of the roof, building-mounted on the rooftop, building-integrated or ground-mounted. Several publications and case studies have shown that such SWTs designed to the
current wind standard and installed in the built environment have issues related to performance and safety [3, 4], underestimated loads, performance degradation and low energy yield [5, 6] and in the worst case scenario, premature failure [7]. The highly turbulent inflow and unsteady flow features of urban wind require specific design consideration for SWTs to operate them safely and yield a reasonable power output in such a low speed and turbulent wind resource.

There has been a reasonable amount of uncertainty in establishing the performance of SWTs in the built environment due to the limited understanding of the turbulence and the turbine’s response to it. Their inconsistent performance and sometimes failure may be due to insufficient statistics that describe atmospheric turbulence in urban wind conditions and inadequate design consideration thereafter. Factors such as morphology of the urban location, low mean wind speeds, sudden changes in wind direction, extreme wind speed fluctuations and extreme wind events, unusual wind shear, change in atmospheric stability, etc. degrade the performance of turbines in built environment [8]. Such salient features of wind conditions in the built environment are not incorporated in the wind turbine design standard IEC 61400-2. Although IEC 61400-2 annex [M] includes such extreme urban wind conditions as other wind conditions and advises that the standard wind condition model is no longer valid for the use by the designer without modification, it is purely an informative Annex and does not provide any alternative suggestions to design turbines for urban wind conditions. The current IEC 61400-2 design standard, prescribed for open terrain installation of SWTs, suggests the use of von Karman and Kaimal spectral density functions in models to simulate wind flow fields that can be used to calculate design loads and predict the structural loading of SWTs [2]. However, Tabrizi et al. [2] showed that both standard models underestimate the magnitude of the power spectra of the measured value for all wind components in the urban sites, thus requiring improvements in the model in IEC 61400-2 to accurately reflect the urban wind condition [9]. There is a gap in the literature in terms of sufficient detailed knowledge of the characteristics of wind fields, compared to open terrain wind fields that the standard models are based on, and their impact on the dynamics of a SWT.

This paper investigates the characteristics of incoming wind flow fields on a rooftop of a building compared to flow over flat terrain in terms of turbulence intensity and intermittency by using higher order statistics. The measured wind data from the two types of terrain is then used to simulate the loading on a 5 kW horizontal axis wind turbine using the aeroelastic code, FAST (Fatigue Aerodynamics Structures and Turbulence) [10]. The predicted performance and loading of the turbine in open terrain and built environment wind conditions are compared with each other as well as benchmarked against predictions using the current IEC standard for SWTs, to highlight deviations that can give insight into how to address the limitations in the standard.

2. Theory

The IEC 61400-2 standard uses a normal turbulence model (NTM) to describe turbulence and turbulence intensity, with the relationship between longitudinal turbulence and wind speed given by:

$$\sigma_{u,90\%} = \frac{I_{15}(15+a\bar{U})}{(a+1)}$$  \hspace{1cm} (1)

where $\sigma_u$ is the standard deviation of longitudinal wind speed, $I_{15}$ is the characteristic longitudinal turbulence intensity (TI) at $\bar{U}=15$ m/s, ‘$a$’ is a dimensionless slope parameter, and $\bar{U}$ is the magnitude of the three-dimensional wind speed at the hub averaged over ten-minute period. The characteristic longitudinal turbulence intensity is expressed as the 90th percentile of longitudinal turbulence intensity measurements binned with respect to wind speed, assuming a Gaussian distribution. The values of $I_{15}$ and ‘$a$’ as 0.18 and 2 respectively are also mentioned in the standard. Upon invoking these values, equation (1) reduces to:

$$\sigma_u = 0.9 + 0.12 \bar{U}$$  \hspace{1cm} (2)

Equation (2) can be rearranged in terms of longitudinal turbulence intensity, $I_u$, as:

$$I_u = \frac{\sigma_u}{\bar{U}} = \frac{0.9}{\bar{U}} + 0.12$$  \hspace{1cm} (3)
When it comes to interpreting the characteristics of wind, it is also equally important to gather and understand the required statistical information and spatial variability of the wind resource. Each interval in a wind speed time series, measured at a particular location, is comprised of a mean speed, $\overline{u}$, and random fluctuations, $u'(t)$, (turbulence) around it, for that time interval.

$$u(t) = \overline{u} + u'(t)$$  \hspace{1cm} (4)

This equation can be rewritten for fluctuation as:

$$u'(t) = u(t) - \overline{u}$$  \hspace{1cm} (5)

To consider two-point statistics, the velocity increments, $\delta u(t)$, depending on a time lag $\tau$ is defined as:

$$\delta u(t) = u(t + \tau) - u(t)$$  \hspace{1cm} (6)

The first-order ($\overline{u}$) and second-order ($\sigma_u$) one-point statistics are summarized in TI; however, the measure of TI does not facilitate the chronological and time-indexed trending of wind speed observations [6]. Further, the first two moments give the complete description of the wind field only when the probability density function (PDF) of the wind fluctuation is Gaussian. However, the purely Gaussian statistics of wind field as characterized by IEC 61400-2 spectra is also not reflected in the measured data from the built environment [11]. Numerous field data and lab tests [12-14] have revealed non-Gaussian characteristics of wind speed increments. The turbulent wind has highly intermittent statistics especially for PDFs of the increments of wind fluctuations during a time lag, $\tau$.

3. Methodology

For the characterization of the wind flow conditions, two disparate locations were selected— one on the rooftop of a building in a built environment in Port Kennedy (PK), Western Australia and another in Östergarnsholm (OG) Island, in the open terrain near the shore of the island. Figure 1 shows the locations of the two wind measurement campaigns. Wind data sampled at 10 Hz for a period of 6 months were used to compare the wind characteristics between these two sites and were further used in the aeroelastic simulation of a 5 kW wind turbine. The wind data was measured at the height 14.95 m at PK, and 17 m at OG with ultrasonic anemometer. Datasets between 315°-80° under the influence of tower shadow were removed from OG. The wind data from PK did not require any data filtering. Recently, a hybrid system of two AIRDOLPHIN PROs SWT and 3kW PV panels with battery bank have been installed in the data measurement site of OG island. The hybrid system powers the data logging system and other measurement equipment for the study and data collection of the marine atmospheric layer.

**Figure 1.** Location of wind monitoring sites at (a) Port Kennedy (built environment) and (b) Östergarnsholm (near shore flat terrain)

The first-order ($\overline{u}$) and second order ($\sigma_u$) one-point statistical moments of the wind speeds time series were analyzed, using custom script in Matlab, for these two sites and compared with the modeled conditions from the IEC 61400-2 standard. The horizontal wind speed and standard deviation over the observation period were binned with respect to wind speed using ten-minute averaged records. To understand how wind gusts are related to small-scale turbulence, a two-point statistical
analysis of the wind flow was done by considering the normalized PDF, \( p(\delta u(\tau)/\sigma_u) \), of velocity increments at 3 different wind speed bins- 4-5 m/s, 7-8 m/s and 10-11 m/s, with \( \tau \) ranging from 0.1s to 150s. An intermittency parameter called shape factor (\( \lambda^2 \)) derived from Castaing’s model [15] is used to determine the shape of the resulting PDF [16]. The \( \lambda^2 \) in a simplified form is derived as equation (7):

\[
\lambda^2 = \frac{\ln(F(\delta u_{\tau})/3)}{4}
\]

where \( F(\delta u_{\tau}) \) is the flatness of the increment PDF at given \( \tau \). To compute the incremental PDF and shape parameters, all the wind time series occurring within each of the mentioned wind speed bins were extracted. The velocity increment of each ten-minute wind record was computed and normalized by its standard deviation at each time lag, ranging from 0.1s to 150s. An average PDF of the normalized increments of the dataset within the wind speed bin at each time lag was computed and compared with the corresponding Gaussian PDF at same time lag. Similarly, the shape parameter at each time lag for each ten-minute record was also calculated using equation (7) and averaged out for each time lag for intermittency plot ranging from 0.1s to 150s. The shape parameters for the two sites at 3 different wind speed bins were thus computed. For Gaussian distribution, \( \lambda^2(\tau) = 0 \).

In order to access the effects of different wind conditions and associated intermittency in the wind field on the turbine’s performance, aeroelastic simulation was conducted for a 5 kW Aerogenesis turbine using its detailed aeroelastic model built in FAST (Fatigue Aerodynamics Structures and Turbulence). The FAST model of this turbine was developed by Samuel P. Evans from The University of Newcastle. The structural aspects of the turbine input in FAST to account for the aerodynamic effects were the blade, tailfin and tower. A constant SD7062 airfoil profile including its radial chord and twist distribution was used for the blade. Further information on the turbine and the details of its FAST model and development methodologies can be found in [17] and [18]. Aerogenesis turbine has an average wind speed of 7.5 m/s, rated wind speed of 10.5 m/s and cut-in wind speed of 3.5 m/s. With the hub height of 18 m, this two-bladed turbine has a passive yaw control system achieved via tail fin.

For the aeroelastic simulation of the turbine, wind time series, one typical and one extreme case each, were chosen from 3 wind speed bins, for both the sites, as indicated in Figure 2 and listed in Table 1. From the wind speed bins of 4-5 m/s, 7-8 m/s and 10-11 m/s, typical value sets comprise of the time series having the mean wind speed within the bin and standard deviation lying on the 90th percentile measured longitudinal turbulence fit line. Similarly, extreme value sets have the time series with the mean wind speed within the selected wind speed bin but with higher standard deviation. The choice of the wind speed bins is also consistent with the ones selected for two-point statistical analyses. Thus, 3 typical and 3 extreme inflow wind conditions are selected for both the sites, for each bin. These ten-minute wind data were used in Turbsim to produce a full-field wind time series that served as an input into FAST. Similarly, 3 full-field wind time series were also generated with Turbsim for IEC Kaimal wind model at 4.5 m/s at 32.5% TI, 7.5 m/s at 24% TI and 10.5 m/s at 20.5% TI to compare the measured statistics with that of the standard.

The size of the grid and number of grid points were chosen as per Turbsim User’s Guide [19] to generate a full-field wind series for PK, OG and IEC wind conditions. A grid size of 12 m x 12 m with 18x18 points was used to generate full-field wind data using a random seed number. A separate grid independent test was done to evaluate the adequacy of the chosen size of grid and number of grid points for the stable statistics from FAST output. All the chosen inflow wind conditions were applied at 18 m height equal to the hub-height of the turbine. Altogether, 15 simulations were undertaken to compare the performance and loading of turbine rotor among the measured and IEC standard inflow wind conditions.

4. Results- Wind Characterization

Figure 2 shows the 90th percentile of longitudinal standard deviation of the ten-minute averaged three-dimensional wind speed at PK and OG compared with the IEC standard. The values of the chosen mean wind speeds and their corresponding longitudinal standard deviation are presented in Table 1.
The IEC standard overestimates the measured data from PK at lower wind speeds and underestimates the data at higher wind speeds (>4.5 m/s). For the flat terrain data in OG, the measured data were below the IEC standard for all the wind speeds.

Figure 2. 90th percentile turbulence fit of measured data at (a) Port Kennedy and (b) Östergarnsholm, with typical and extreme cases marked

Table 1. Selected mean values for typical and extreme wind cases and their corresponding standard deviation from PK & OG wind data and IEC

<table>
<thead>
<tr>
<th></th>
<th>Typical Cases</th>
<th>Extreme cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-5 m/s</td>
<td>7-8 m/s</td>
</tr>
<tr>
<td>PK</td>
<td>$\bar{U}$</td>
<td>4.62</td>
</tr>
<tr>
<td></td>
<td>$\sigma_u$</td>
<td>1.54</td>
</tr>
<tr>
<td>OG</td>
<td>$\bar{U}$</td>
<td>4.26</td>
</tr>
<tr>
<td></td>
<td>$\sigma_u$</td>
<td>0.79</td>
</tr>
<tr>
<td>IEC</td>
<td>$\bar{U}$</td>
<td>4.50</td>
</tr>
<tr>
<td></td>
<td>$\sigma_u$</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Figure 3 shows that the longitudinal turbulence intensity ($I_u$) at PK was observed to be higher than that specified by the IEC normal turbulence model (NTM) - about 24% at the characteristic wind speed of 15 m/s. For OG, the longitudinal turbulence intensity was below the standard’s value of 18%, assumed across all wind classes for flat terrain.

Figure 3. 90th percentile fit of measured turbulence intensity of longitudinal wind speed at Port Kennedy and Östergarnsholm

Figure 4. Shape parameter ($\lambda^2$) of the wind speed increments, Port Kennedy and Östergarnsholm at 4-5 m/s, 7-8 m/s and 10-11 m/s

Figure 4 shows the intermittency shape factor versus time lag for the two sites for the three wind speed bin scenarios. For PK, the lower the wind speed bin, the higher the intermittency at small time scale and the longer the decay period at larger timescales. For OG, all three wind speed bins had about same intermittency at small timescale, and the lower the wind speed bin the longer the decay at larger
timescales. For all the three wind speed bins, the PK wind field had higher intermittency at smaller time scales compared to the OG data. As the time lag increased, the intermittency in this built environment wind field (PK) decayed faster than that of the flat terrain (OG).

![Figure 5: Normalized PDF of velocity increments for PK (•), OG (○) and measured Gaussian (—) at wind speed bin of 7-8 m/s at time lag of 0.5s, 10s and 40s](image)

For the wind speed bins of 7-8 m/s, Figure 5 shows the normalized PDF of velocity increments at $\tau = 0.5s$, 10s and 40s for both the sites. Figure 4 shows that, up until $\tau = 2.5s$, the PK wind data has higher intermittency and Figure 5a clearly shows that the Gaussian distribution underestimates the probabilities of large values of fluctuations for both PK and OG, with greater deviations from Gaussian behavior observed for PK. The PK wind data demonstrates both higher turbulence and higher intermittency (observed through the heavy-tailed from the incremental PDF in Figure 5a), indicating the occurrence of frequent gusts and larger probability of the extreme events than predicted by the Gaussian distribution. For time-lags greater than 2.5s, Figure 4 shows that the PK data starts to converge faster than OG data and, at $\tau = 10s$, Figure 5b shows the probabilities of fluctuations for PK are lower than that of OG, although the difference is not significant. At $\tau = 40s$ where PK data converges to a Gaussian distribution, the OG data still exhibits non-Gaussian characteristics (see Figure 5c). In summary, the occurrence of extreme fluctuations was higher for PK at smaller timescales while there was more probability of extreme events for OG at larger timescales. This suggests that the intermittency in the built environment at larger timescales is less likely than in open terrain. The presence of obstacles caused the turbulence to break down into smaller eddies, resulting in high intermittency only at small timescales for the built environment (PK). A similar trend in intermittency was observed for both the sites at the other two wind speed bins—4-5 m/s and 10-11 m/s, where the effect was more pronounced and the values converged faster with increasing mean wind speed.

5. Results- FAST Simulations
The key statistics of interest from the FAST output were rotor torque, rotor thrust, blade root flapwise bending moment (FBM) and generator power. These parameters were computed at 10 Hz for a period of 10 minutes in FAST. The maximum and mean values for these parameters were calculated using typical and extreme inflow wind data from the two contrasting terrain sites as well as from the IEC standard Kaimal model. Aerogenesis’ rated power is 5 kW and the braking mechanism activates during the event when generation exceeds 5 kW, which is not modelled in this FAST model. In terms of mean generator power, there is a slight variation among the 3 typical inflow cases, as seen in Figure 6a. The electrical power with the IEC Kaimal wind field at 10.5 m/s was 6045 W while that with PK and OG were 6102 W and 5980W, respectively. Notably, this was around 1000 W greater than the normal rated power of 5 kW at 10 m/s that may be related to the passive power control methods used in the FAST model of the turbine. Also, the generator power with extreme wind case at 10 m/s from both PK and OG wind sets was 2kW higher. The elevated turbulence level in the inflowing wind appears to affect the turbine’s power generation. Lubitz [20] found that increased turbulence at low wind speed increased energy production however, at turbine’s near-furling wind speed, the elevated
turbulence decreased the energy production. So, within the turbine’s operating range, the increased turbulence appears to increase the power production of the turbine.

![Figure 6](image)

Figure 6. (a) Mean generator power with measured typical and extreme cases compared with IEC standard and (b) simulated longitudinal turbulence intensities

Figure 6b shows the simulated values of longitudinal turbulence intensities (TI) in PK, OG and IEC wind cases for typical and extreme values at 3 wind speed bins. With Aerogenesis’ design wind speed of 10.5 m/s, the increased turbulence at the turbine’s operating speeds should increase the energy production. It can be noted in Figure 6b that the TI with typical cases in the PK wind at all the wind speed bins are higher than that of the IEC while the OG wind cases have TI below the IEC values. This corresponds to the PK wind generating power slightly greater than the IEC wind at all 3 wind speeds bins and the generator power in OG wind being less than that in IEC wind. The extreme wind cases produced more electrical power for both the sites. Interestingly, the extreme wind cases have the TI values higher in the OG wind than in PK wind. Thus, the mean generator power in OG wind with extreme wind cases is higher despite the extreme PK wind datasets having mean wind speeds that are higher than the extreme OG data (refer Table 1). With exception of the extreme wind cases, the mean generator power in PK wind primarily with typical cases can be expected to be higher than both IEC and OG wind cases because the mean longitudinal turbulence intensity at PK is seen, as in Figure 3, to be higher than that estimated by the IEC standard.

![Figure 7](image)

Figure 7. Ten-minute statistics for (a) maximum and (b) mean rotor thrust and blade root FBM

Figure 7a, 6b compare the ten-minute maximum and mean values of rotor loads from simulations using PK and OG wind data with the IEC wind data for both typical and extreme cases at the selected 3 wind speed bins. For the typical wind case, the maximum and mean values of rotor thrust and blade root FBM are greatest for the PK wind case, followed by the IEC wind case and OG wind case, at all 3 wind speed bins. However, with the extreme wind cases, the PK wind has maximum values of the rotor thrust and blade FBM than the other two while the OG wind cases have the higher mean values for these loads (Refer Figure 7b). Figure 7a depicts that the maximum rotor thrust loads are higher than the IEC wind values for PK data for both typical and extreme wind conditions at all three mean wind speed bins. A visible increase of 11% and 32% in rotor loads are observed at 4-5 m/s for PK with typical and extreme wind cases. Likewise at 7-8 m/s, there is an increase in rotor thrust of 11% and 42%. Similarly, there is also an increase in maximum blade root flapwise bending moment (FBM) of 8% and 36% with typical and extreme wind cases, respectively. More significantly, the maximum
rotor thrust was 89% higher and blade FBM was 91% higher than the IEC values for the PK wind case with extreme values at 10-11 m/s wind speed bin. On the contrary, the predicted values for the extreme wind cases for OG did not exceed the values for the IEC wind cases, except for the 7-8 m/s bin, where there was an increase of 29% in rotor thrust and 17% in blade FBM.

An inspection into the corresponding time series of the wind cases revealed that the velocity components in the PK wind data have higher sampled values resulting in higher wind fluctuations within the ten-minute record. Additionally, the mean turbulence level in the PK data was higher than that assumed by the NTM in IEC 61400-2 standard. The fatigue loadings appear to be more closely associated with instantaneous values of rotor loads than the ten-minute averaged loads. The PK wind cases have higher fluctuations and greater turbulence and thus render higher magnitudes of instantaneous rotor loads. Given the large maximum rotor loads predicted in the PK wind cases, it is more likely that the turbine at PK will suffer higher damage loading and have shorter working life than the same turbine at OG. Calculation of damage equivalent load for the blade flapwise bending moment load would give quantitative comparison of potential fatigue loading due to different inflowing wind conditions.

![Figure 8](image_url)

**Figure 8.** Time series plot and power spectra of blade root FBM response for PK, OG at 7-8 m/s, for (a) typical and (b) extreme cases compared with IEC

During the operation, a wind turbine’s blades are loaded in the flapwise and edgewise (lead-lag) directions. For a SWT, the blade fatigue in the flapwise direction is more severe than the edgewise direction due to relatively low sectional stiffness and high aerodynamic moment when compared to lead-lag direction [21]. Figure 8 presents comparative time series plots for PK, OG and IEC of the blade root FBM for a ten-minute simulation period for typical and extreme wind cases. Higher instantaneous blade loads were observed for PK for the typical case while the blade loading for OG was more uniform and remained below the IEC loads. The corresponding power spectral densities (PSD) depict the blade response in the frequency domain. A once-per-cycle (1P) response could be observed in the flapwise bending moment spectra between 3-4 Hz corresponding to the fundamental rotor frequency.

The extreme wind cases exhibited higher instantaneous blade loads for both PK and OG sites (Refer Figure 8b) and thus a higher magnitude of 1P response. This increased blade loading can result in higher fatigue and loading of the turbine’s blades than estimated by the IEC standard. Similar 1P responses pertaining to the blade passing frequency were observed for other inflow wind cases with typical and extreme values at other wind speed bins. With the output of FBM statistics at 10 Hz resolution, the PSD was clipped at 5 Hz and no other significant peaks could be observed that may be related to the effects other than rotor’s basic frequency of rotation. Further research to address this would require wind measurements and FAST simulations for a higher frequency than 10 Hz.

6. Conclusion

This work involved analyses on measured wind fields from two disparate terrain types in terms of turbulence, intermittency and the effect of these wind fields on the predicted performance and loading
of a horizontal axis SWT using the FAST aero-elastic code. A 90th percentile fit of measured data revealed that wind data from the Port Kennedy (PK) built environment site yielded a characteristic longitudinal turbulence intensity (at hub height wind speed of 15 m/s) of 24%, significantly higher than 18% assumed in IEC 61400-2 standard for SWTs. The flat terrain wind data from Östergarnsholm (OG) Island had the turbulence intensity values below the IEC standard for all the wind speed.

From an analysis of the two-point statistics of wind speed increments, PK wind data showed higher intermittency than OG wind set at smaller time scale for all chosen wind speed ranges. In contrast to the flat terrain wind data from OG, the intermittency in PK wind data decayed faster at the larger time scales. The PDF of wind speed increments revealed the occurrence of more extreme fluctuations for the PK wind data at smaller timescales and for OG at larger timescales. The rate of decay of intermittency was faster with increasing mean wind speed. The literature suggests that intermittency effects do get passed on to influence a turbine’s loading but in this study, the chosen statistics from FAST could not suitably relate to the intermittency effect in the wind data sets from these two disparate sites. Further simulations are required using more wind data before drawing any conclusions as to the influence that intermittency has on the power performance and loading on the turbine.

From the predicted performance of the turbine, the typical inflow wind conditions from both the sites showed mean electrical power output varied slightly with the predictions based on IEC 61400-2 standard wind conditions, for all the selected wind speed bins. For the extreme wind cases, the OG data produced more mean generator power output than the IEC wind with increases of 64% at 4-5 m/s, 43% at 7-8 m/s and 24% at 10-11 m/s. Simulations with the PK wind data also predicted higher mean generator power values than the IEC wind case for extreme data but lower than that from OG. Similarly, the OG wind had higher mean rotor loads for rotor torque and blade root FBM, whilst the PK wind cases demonstrated increased maximum rotor loads. This needs further investigation with more extreme ten-minute data records but it appears the increased turbulence and higher fluctuation in PK wind leads to higher maximum rotor loads even though the mean loads are lower than the OG data. The ultimate rotor thrust and blade root FBM with PK wind (extreme cases) were 89% and 91% higher than that estimated using the IEC wind data. The higher value of blade root FBM is likely to induce higher damage loads that will eventually shorten the working life of the turbine blades at such built environment sites. Evaluating the PSD plot of the blade root FBM, no other significant dynamic effects were observed other than the rotor passing frequency (1P response) for all the wind cases at both the sites.

This study can be extended further by investigating more typical and extreme cases of inflow wind conditions at different wind speed bins from both the sites and predicting the damage equivalent fatigue loading to quantify the effect of urban wind conditions on blade loading. Overall, this research suggests that urban wind fields have higher turbulence intensity and pose higher loading on the turbine rotors than estimated by the IEC 61400-2 standard. The wind models assumed in the current IEC 61400-2 for SWTs are not adequate for the turbines to be sited in the built environment and the standard requires revision to make it more inclusive of urban wind fields. The current standard clearly underestimates the urban wind conditions both in terms of turbulence intensity and performance/loading for the wind conditions in the built environment.

Acknowledgement
The authors would like to acknowledge Dr. Samuel P. Evans and Dr. Phil D. Clausen from the University of Newcastle, NSW, Australia for providing the FAST model of 5 kW Aerogenesis wind turbine and their feedback on the FAST results. Anup KC is grateful to Murdoch University for the MIPS award during his PhD candidature and DAAD for the grant during his research stay at ForWind, University of Oldenburg, Germany. Many thanks to Hans Bergstrom from Uppsala University for providing the Östergarnsholm wind data sets.
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