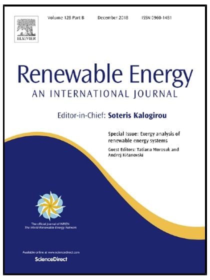

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Anup KC, Jonathan Whale, Tania Urmee

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Urban wind conditions and small wind turbines in the built environment: A review

Anup KC[a,], Jonathan Whale[a], Tania Urmee[a],*

[a]*School of Engineering and Information Technology, Murdoch University, Perth 6150, WA, Australia*

***Corresponding Author:**
Anup KC
School of Engineering and Information Technology,
Murdoch University, South Street, Murdoch, 6150
Western Australia
Tel: + 61 8 9360 6244
Email: a.kc@murdoch.edu.au

Abstract

Wind conditions in the built environment are complex in nature and characterized by lower wind speeds and higher turbulence due to the presence of obstructions. A growing body of literature and research/testing activities related to performance evaluation of small wind turbines (SWTs) in urban wind conditions have inferred that urban installed SWTs are subjected to higher level of turbulence and face dynamic loading that impedes their performance, and reduces fatigue life. This paper reviews the diverse studies conducted on the application of SWT technology in the built environment to understand the characteristics of inflowing wind, their performance and identify the gaps in the knowledge. This review paper also investigates the extent to which the international design standard for SWTs, IEC 41400-2, is valid for urban installations. The findings from this review show that the wind models incorporated in IEC 61400-2 is not suitable for installation of SWTs in the built environment. The authors recommend a thorough study through measured data and characterization of urban wind to make current standard inclusive of wind classes that characterize urban wind conditions. Thus, SWT design can be made more consistent with urban wind conditions and their performance and reliability can be assured.

Keywords: Small wind turbines; built environment; IEC61400-2; intermittency; elevated turbulence; fatigue loading

Nomenclature

a	dimensionless slope parameter
ABL	atmospheric boundary layer
AEP	annual energy production
AMWS	annual mean wind speed
BMWT	building-mounted wind turbine
BWT	built-environment wind turbine
CFD	computational fluid dynamics
CTRW	continuous time random walk
DEL	damage equivalent load
GW	Giga Watt
HAWT	horizontal-axis wind turbine
HIT	homogeneous isotropic turbulence
I	turbulence intensity
I_u	longitudinal turbulence intensity
I_{15}	turbulence intensity at hub-height wind speed of 15 m/s
IEA	International Energy Agency
IEC	International Electrotechnical Committee
k	turbulence kinetic energy, $[m^2/s^2]$
LES	large eddy simulation
MM5	Fifth-Generation Penn State/NCAR Mesoscale Model)
MMK	Murakami–Mochida–Kondo
MW	Mega Watt
NTM	normal turbulence model
PDF	probability density function
PSD	power spectral density
PV	photovoltaic
RNG	Re-Normalization Group
RSL	roughness surface layer
SA	Sparlart Allmaras
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SST	shear stress transport
SWT	small wind turbine
TC	thermal collector
TC	technical committee
URANS	Unsteady Reynolds Averaged Navier-Stokes
VAWT	vertical-axis wind turbine
WEC	wind energy converter
WRF	weather research and forecasting
WTPC	wind turbine power curve
σ_u	standard deviation of longitudinal wind velocity
$\sigma_{u,90pc}$	90th percentile of the standard deviation of longitudinal wind velocity
λ	intermittency parameter
Δt	time interval, 10-minute
τ	time lag between two fluctuations, [s]
$\overline{U}$	wind speed in longitudinal direction, averaged over 10-minute interval, [m/s]
u(t)	wind speed time series in longitudinal direction, [m/s]
u'(t)	wind speed fluctuations in longitudinal direction, [m/s]
V_{avg}	annual average wind speed at hub height, [m/s]
V_{ref}	reference wind speed averaged over 10-minute, [m/s]

1. Introduction

With rapid growth in population, the global energy consumption is projected to increase by 56% between 2010 and 2040 [1]. In 2015, fossil fuel (coal, petroleum and natural gas) accounted for 78.4% of global final energy consumption, with the share of renewables (modern and traditional) and nuclear power at 19.3% and 2.3% respectively[2]. Worldwide, the share of renewable energy will increase to address global climate change by 2030. Modern renewable energy is being used increasingly in four distinct markets: power generation, heating and cooling, transport fuels, and rural/off-grid energy services [3]. In recent years, progress has been made in increasing the renewable energy share in the power sector particularly in the wind, solar photovoltaic (PV) and hydropower sectors [4]. In 2014, the total renewable power capacity was 712 GW out of which 370 GW was from wind energy through utility scale wind turbines [5]. The total global capacity of wind energy reached 432 GW at the end of 2015, representing a cumulative growth of 17%. Although large-scale generation using wind energy has taken shape, there are some problems for their sustainable development. For example, the main barriers of large scale on-shore wind farm are available sites, impact of grid power quality, public acceptability and losses in transmission and distribution of electricity to the consumers [6]. One alternative that reduces some of these barriers is the application of small wind turbine (SWT) technology.

There is a noticeable increase in the installation of SWTs with the global capacity reaching 830 MW at the end of 2014, which is 10.9% more compared to 2013 [7]. It is also projected that the global installed capacity of SWTs will reach 2000 MW by 2020 which is creates a lucrative small wind energy market for both manufacturers and researchers. With their increasing abilities in harnessing the wind resource, SWTs in urban areas, e.g. built-environment wind turbines (BWTs), and building-integrated or –augmented wind turbines (BUWTs/BIWTs) building-mounted wind turbines (BMWTs) are also gaining popularity along with their commercial open-terrain and offshore counterparts. Such environment-friendly and cost-effective modern small SWTs are ideal for generally functioning as an energy source to meet household electricity demands for lighting, small telecommunication centres and mobile homes [8].

Recent developments in wind energy technology and studies on turbine design and wind characteristics have shown the promising opportunities for installing SWTs in the built environment. Wind turbines installed in such areas can be either vertical-axis wind turbines (VAWTs) or horizontal-axis wind turbines (HAWTs). The most suitable type of turbine depends on the cut-in wind speed, flexibility in installation and operation, height-limit and aesthetic integration with the existing morphology in the built environment. For instance, in HAWTs, the tracking of wind direction is necessary, while for VAWTs the fixed rotation axis makes them more visually appealing. The wind potential in the urban environment and the associated technology to harness wind energy through common types of wind turbines are discussed in [9, 10] via different case studies. These studies concern the feasibility of urban installed wind turbines to demonstrate the viability of larger market uptake [11] for such installations and highlight the wind flow characteristics in the urban settings [9]. Islam et al. [12] presented a detailed literature review on the physics of wind energy, wind power meteorology and the technological development that broadened the market potential for wind systems. Emphasizing the significant contribution to energy requirements in the built environment, Dutton et al. [13], in their feasibility study of building mounted wind turbines, summarized the important technical hurdles and medium priority actions for deployment of such turbines in urban environments. In terms of technical challenges, the effect of urban landscape on the wind profile, design of the turbine components to cope with elevated turbulence levels and issues about safety/vibration/noise are of prominent concerns. Additionally, issues related to reliability and capital cost, design optimization and maintenance are also important when siting the SWTs in the built environment.

Compared to rural areas with open terrain, the urban wind regime is characterized by low annual mean wind speeds (AMWS) and more turbulent flow occurring in the atmospheric boundary layer (ABL) due to the rapidly changing wind direction and presence of obstacles. The low AMWS stems from the uneven ground topography/ obstacles, while the increased turbulent flow is the result of wind interacting with buildings and obstacles [14, 15]. Figure 1 is a graphical representation of how wind speeds varies in speed and direction due to the presence of upstream obstacles and the effect of turbulence at average wind speed. Most of the SWTs installed in the built environment are sited with a limited understanding of the wind conditions of the candidate location and the influence of surrounding topography. Such atmospheric turbulence is superimposed on the wind’s average motion and it impacts the wind energy converter (WEC) in many ways, e.g. unexpected downtimes due to failure during operation, fatigue damage, inconsistent power output etc. [16]. Despite the advanced manufacturing process and design techniques of wind turbines, the physics of turbulent wind in the built environment and its related statistics during interaction with SWTs are still not known sufficiently. Lack of understanding of local wind conditions produced by the stochastic wind interactions with localized structure have resulted in poor siting and improper use of such SWTs impede safety, durability and performance [17].

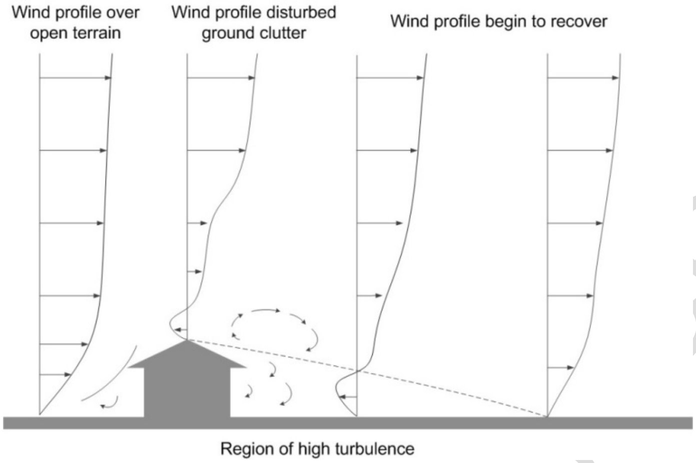

Figure 1 Effect of turbulence on oncoming wind profile, adapted from Suchada, J. [18]

This paper provides an extensive review of SWT research and aims to understand the nature of urban wind flow, its adequate characterization, its effect on SWT's performance and loading and their location of installation in the built environment. This review also discusses the inherent complexities and challenges associated with the installation of SWTs in the built environment and the suitability of the current international design standard *IEC 61400-2 Part 2 Design requirements for small wind turbines* [19] for SWTs. The aim of this paper is to:

- Understand the inflow to SWTs installed in the built environment, and the gaps in our knowledge
- Understand the performance, in terms of loading and power output, of SWTs installed in the built environment
- Understand the influence of buildings in the urban wind flow fields to figure out appropriate siting of rooftop SWTs to improve their performance
- Examine the current international design standard for SWTs and understand to what extent this standard caters to installation in the built environment

Section 2 of this review discusses the applicability of the current wind standard for SWTs to be sited in the built environment. The constraints of direct wind data measurement in urban areas and alternative numerical approaches are discussed in Section 3. The turbulent nature of urban wind is discussed in Section 4. Likewise, the intermittency in the turbulent wind field in the built environment and its characteristics are discussed in Section 5. Section 6 explores the influence of shapes of the buildings and urban topography on the incoming wind profile of rooftop installed SWTs. Issues with power performance and fatigue loading of SWTs in the built environment are presented in Section 7 and 8 respectively. In the discussion section, the authors have identified the gaps in our understanding of the wind conditions in the built environment and their impact on SWTs, thereby identifying areas for further research effort.

2. Small wind turbines in the built environment and current IEC standard

Wind turbines are designed for safety, durability and performance according to the international standard IEC 61400 series. These standards describe the wind field models, occurrence of turbulence and extreme events that are required by wind turbine manufacturers to predict the design loads on turbines. The IEC 61400-2 standard defines SWTs as wind turbines that have a swept area of < 200 m^2 [19]. Generally, SWTs installed in the built environment have a smaller rotor size so that their size does not interfere with the extended region of the vertical wind profile. SWTs of this size are dynamically rigid, thus small changes in local forces will affect the entire system. Unlike a VAWT that can cope with the fluctuating wind direction, the performance of a HAWT is highly dependent on the direction of the wind and its magnitude [20]. Such turbines operate on the basis of a few passive control principles (for aligning the rotor with the wind direction, braking, and furling to prevent over speed during high winds) and the majority are devoid of a pitch control system [21]. This results in the blades and tower bearing most of the fatigue loading on the turbine. Horizontal-axis SWTs face operational complexities when installed in the built environment due to fluctuating wind speed and, most importantly, elevated levels of turbulence which are site-specific and are largely affected by the geometry of the buildings and ground topography [22]. The terrain features can produce unusual wind shear and significantly affect the level of turbulence and the overall energy output from the turbine. The higher the turbulence, the stronger a turbine structure needs to be in order to withstand the instantaneous and long term fatigue loads as well as extreme wind events.

The standard IEC 61400-2 specifies design loads for small turbines installed in open and flat terrain including the design, installation, maintenance and operation. It suggests the use of von Karman and Kaimal spectral density functions [23] in turbulence models to simulate wind flow fields that can be used to calculate their design loads and predict the structural loading of SWTs [24]. Both spectra are based on observations of wind conditions over open and uniform terrain; the von Karman spectrum was derived for isotropic turbulence and the Kaimal spectrum was derived from atmospheric measurements. The design requirements for small wind turbines are defined by IEC 61400-2 in terms of wind speed and turbulence parameters. The standard uses a Normal Turbulence Model (NTM) to describe turbulence and turbulence intensity that includes the effects of varying wind speed and varying direction. In the same standard, the 'characteristic turbulence intensity', *I,* is defined as the 90th percentile of longitudinal turbulence intensity measurements, conditional on mean wind speed, assuming a Gaussian distribution of wind fluctuations. The IEC 61400-2 defines four different standard SWT classes (I-IV) to describe the external conditions of the various types of the sites as shown in Table 1. These classes typify a range of site with wind conditions that a SWT may experience from normal to very high average and maximum wind speeds with turbulence intensity considered a constant value for all wind classes.

Table 1 Basic parameters for the standard SWT classes I-IV, s to be described by the manufacturer (IEC 61400-.2- 2013)

		Wind Turbine Classes				
Basic Parameters		**I**	**II**	**III**	**IV**	**S**
V_{ref} (m/s)		50	42.5	37.5	30	Value to be specified by the designer
V_{avg} (m/s)		10	8.5	7.5	6	
A	I_{15} (-)	0.18	0.18	0.18	0.18	
	a	2	2	2	2	

V_{ref} is reference wind speed averaged over 10 minutes.

V_{avg} is annual average wind speed at hub height

I_{15} is characteristic value of hub height turbulence intensity (ratio of wind speed standard deviation to mean wind speed) at a 10-minute average wind speed of 15 m/s

'A' is turbulence class having dimensionless slope parameter, 'a', for turbulence standard deviation model to be used in Equation 2 of this review paper

Based on the data reviewed by the IEC Technical Committee (TC) 88 [25], two turbulence classes, A (with parameter 'a' as 2) and B (with parameter 'a' as 3), were defined to represent sites with high and moderate turbulence respectively. It was also agreed that wind speeds ranging from 10 m/s – 25 m/s and in particular the values of turbulence intensity in this wind speed range, are the most important for both fatigue and ultimate loads. In case any special design is required, an ‘S’ class is also available to address the special conditions, still the built environment composes a very specific and peculiar site for wind turbines such that these parameters are not sufficient enough to achieve acceptable reliability and design safety levels.

The standard also presents a wind field model that describes the external wind conditions in terms of turbulent fluctuations and extreme wind events. Such conditions are quantified by stochastic turbulence models that are used as inputs to aero-elastic codes to predict the thrust forces and bending moments on the turbine. The IEC 61400-2 allows for the use of either von Karman or Kaimal spectral density functions [23] to simulate the flow fields, calculate design loads and predict loadings on the turbine [24]. This wind model was developed semi-empirically using data from the flat, open terrain of Kansas, USA and specifies a characteristic turbulence intensity that is valid for wind speeds in the range of 10 m/s – 25 m/s [25]. The wind flow field around turbines in the built environment, e.g. ground-mounted in peri-urban areas or rooftop-mounted in industrial estates is different compared to the conventional locations assumed in the standard. Wind distribution in open terrain is almost two-dimensional but the built environment is also comprised of large vertical components as wind moves past the obstacles/buildings.

As the range of installation sites expand from conventional open terrain to include the built environment, the SWT design standard needs to be expanded to include wind classes that characterize the urban wind conditions, i.e. wind conditions that currently lie outside the range of wind conditions adopted in IEC 61400-2. The current situation is that turbines are being designed as per the IEC standard pertaining to the open terrain but are then installed in the built environment, resulting in issues related to performance and safety [26-28]. The cyclic nature of fluctuating blade loads may cause fatigue loading and the results are underestimated loads, performance degradation and low energy yield [22, 29], and in the worst case scenario, premature failure [30-33]. Inconsistent performance and failure of wind turbines in the built environment may be due to insufficient statistics that describe atmospheric turbulence in urban wind conditions and inadequate design consideration thereafter. Factors such as the morphology of the urban location, low mean wind speed, sudden change in wind direction, extreme wind speed fluctuations and wind events, unusual wind shear, change in atmospheric stability, etc., degrade the performance of turbines in built environment [17, 34]. 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 '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 address the urban wind condition~~s~~. The fixed values of turbulence intensities used in standard NTM, as shown in Table 1 with respect to wind classes for SWTs, ~~also~~ may also not be applicable particularly for urban areas because of uneven terrain and presence of different obstacles.

The wind conditions in the built environment differ greatly from that in undisturbed locations such as open terrain in terms of mean speed and turbulence. So, if their performance and durability are to be ensured, the turbines to be installed in such locations must be designed in accordance with the inflow that they will experience. The current wind standard IEC 61400-2 does not incorporate the peculiar wind flow features in the built environment. In order to predict the effect of urban wind fields and cater to the design of the turbines to function satisfactorily in the urban settings, one must possess enough knowledge to interpret the behaviour of the urban wind, the turbulence, and its proper statistical description.

3. Urban wind resource assessment and constraints in direct wind data measurement

The urban wind energy resource is yet to be exploited efficiently due to lack of detailed resource assessment studies [35]. Although, an onsite measurement campaign may not be necessary for SWT sites with good exposure to prevailing wind directions and without major obstacles within at least several kilometres, this is not true for built environment sites [17]. One of the main constraints in understanding wind flows in urban areas is the lack of adequate field measurements which could help characterize urban wind and understand its effect on turbines [36]. The WINEUR project report [37] in 2007 recognized the need for direct measurement of wind data, although time consuming and expensive, for accurate prediction of annual energy production (AEP). The report, however, did not provide a monitoring method for urban wind resource assessment and the procedure followed in the report for wind monitoring emulates the procedure used in resource assessment for large-scale wind farms. Fields et al. [34] recommended some key considerations to be incorporated during the technical evaluation of urban SWT projects such as wind resource assessment, turbine siting, turbine specification and energy production, and safety and reliability of the turbine. They recommended the onsite atmospheric measurement as the best option to quantify the wind resource. However, accessing the wind resource in the built environment is the most challenging element of an urban SWT project.

For medium to large-scale wind projects (wind farms), the local wind resource and its characteristics are studied extensively by producing detailed, high resolution and accurate wind maps, as well as identification of uncertainty and turbulence related to the wind resource [38]. From an economic point of view, such resource assessment only claims a small portion of the total budget of the project but can be very costly for built environment SWT projects in terms of the proportion of the cost [39]. For this reason, site-specific ‘regional assessment’ of wind resource and wind characterization in urban or peri-urban areas through in-situ measurement is not a common practice for SWT [34]. Further, the measurement of wind data is relatively difficult for complex terrain due to the stochastic nature of wind which does not follow any known statistical distribution and demands a high-temporal resolution of logged data to be able to capture the significant additional energy present in the turbulent wind resource in urban locations [40]. Limited budget and lack of site-specific measurement increase the level of uncertainty during the performance assessment of the SWTs making further analysis of the interactions of the WTs with the local loads and distribution network even more difficult [38]. Such constraints may be addressed by employing numerical simulation of wind flow and turbulence with the help of different computational fluid dynamics (CFD) tools.

With the advancement of numerical methods and computational resources, the application of CFD in numerical studies on wind flows has become common practice and is often used to fill in the gap created by inadequate data measurements and to study the behaviour of wind in and around the built environment. Nonetheless, they still require significant computational resources and extended time period followed by experimental validation to prove their accuracy. Advanced modelling approaches such as large eddy simulation (LES) may capture the full array of flow physics but are expensive to run, potentially costing more than the small wind turbine itself [34, 36]. Although such high-resolution models can interpret larger-scale flow structures in urban environment, these numerical models have limited representations of small-scale structures and the details of such flow structures are difficult to simulate [17]. Moreover, the construction of the domain geometry is difficult/complex during urban wind modelling in CFD and the convergence problems often introduces errors in the results [36].

There are comparative software studies that have modelled the flow patterns in complex terrains [41] , [42], [43], forests, steep mountains and valleys [44], [45] or wakes [46, 47]. Such numerical results are largely sensitive to the boundary conditions and computational parameters set by the user and a comparison of numerical results with measured data is always desirable to verify the accuracy of results.

Kalmikov *et al.* [39] considered the complex geometry of an urban area using the UrbaWind CFD model to evaluate the wind energy potential of the candidate location and for better representation of turbulence and wakes on wind flow around the buildings in urban areas. They compared the meteorological data measured at the site with the CFD simulation which exhibited satisfactory agreement. Similarly, Sanquer et al. [48] applied UrbaWind to model wind in a dense urban environment. They assessed wind pedestrian comfort and ventilation in urban areas and the numerical results matched well with the experiments. Fahssis et al. [49] modelled a complex rural terrain in UrbaWind that considered the vortex and venturi effect created by buildings, porosity of the trees and the effects of the ground roughness. The model also produced comparable results, differing by 8.5% with the experimental measurements. However, Ayala et al [50] applied both UrbaWind and the wind atlas computational code WAsP to study the wind power resource in complex terrain wind farm and found that both the simulation results underestimated the actual annual production. Similarly, Simões et al. [51] concluded that data sources from mesoscale (MM5, WRF) and microscale models (WAsP) are not adapted for urban wind characterization as these models do not account for the effects of urban wind conditions and often tend to overestimate the wind potential in such built environment.

Currently, in the absence of proper monitoring guidelines and simple inexpensive CFD codes, some standard assumptions and extrapolation from limited data are followed for SWT installations which typically overestimate the turbine's performance [34, 38]. Different probability distribution functions (PDFs) such as Weibull, Rayleigh and Lognormal functions are commonly used as a fit to the measured wind speed frequency distribution in a given location over a certain period of time. Although it is a common practice to compare these functions to determine which one fits the measured distribution the best in a particular location, the Weibull function has mostly been used to fit wind speed distributions [52]. Carrilo et al. [53] and Seguro et al. [54] have discussed the methods of calculating the parameters of the Weibull distribution for wind energy analysis in producing the best results for energy production of a WEC. However, Smith et al. [17] highlighted the non-Weibull probability distributions of the wind flows in urban locations that are further modified due to the presence of blockades and diversions, insisting on the need for high-resolution, three-dimensional wind measurements in the built environment.

Since 2013, the International Energy Agency (IEA) Wind Task 27 [55] has been documenting all the research and testing activities related to SWTs soliciting through its participant countries wind and turbine data of SWTs in urban areas. The documented results of turbulence in urban winds from various researchers and participants are expected to establish a new recommended practice for the micro-siting of SWTs in the built environment. The upcoming report aims to address the special resource assessment required for the built environment and the special testing and design standards needed for SWTs operating in such locations.

4. Urban wind and turbulence in the built environment

Although SWTs are slowly gaining popularity in urban installation, studies on the nature of urban wind and the performance of the turbine in such wind conditions have not been conducted rigorously. There has been a very little study related to understanding the dynamics of urban wind and its effect on the performance and integrity of SWTs installed in such environment. This is discussed in the following sections.

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.

$$u(t) = \overline{U} + u'(t) \qquad \text{Equation 1}$$

The estimation of turbulence strength in the time interval, Δt, is given by the turbulence intensity (I), as shown in Equation 2, which is a basic measure of the overall level of turbulence and how variable the wind flows are.

$$\boldsymbol{I} = \frac{\boldsymbol{\sigma_u}}{\overline{\boldsymbol{U}}} \qquad \text{Equation 2}$$

where $\sigma_u = \sqrt{\frac{1}{N_s - 1}\sum_{i=1}^{N_s}\left(u_i - \overline{U}\right)^2}$

with σ_u , the longitudinal standard deviation of wind speed variations at hub height. 'I' is largely a function of atmospheric stability, elevation and roughness length.

Issues related to urban wind conditions such as elevated turbulence, intermittency in turbulent wind and extreme events started drawing noteworthy attention from researchers from 2010 onwards. Before 2010, a few studies [56-59] were available on the prospects of SWTs and the complex wind conditions in urban environment. Mertens [60] highlighted the problems with urban wind conditions having low average wind speed and high turbulence in relation to power generation. After 2010, issues pertaining to urban wind resource assessment, the effect of turbulence on fatigue loading and power curves, characterization of urban wind and design optimization of turbine blades in relation to its installation in urban areas began to draw the attention of the researchers. Some significant research has been conducted related to the effect of turbulence on wind turbines, power performance, fatigue loading and wake generation of WTs installed in open terrains or wind farms which are discussed in later sections of this review.

As stated in Section 2, the IEC 61400-2 has the NTM applicable for small wind turbines to describe turbulence and turbulence intensity, with the relationship between longitudinal turbulence and wind speed given as in equation 3:

$$\sigma_{u,90pc} = \frac{I_{15}(15 + a\overline{U})}{(a + 1)} \qquad \text{Equation 3}$$

where 'I_{15}' is the characteristic longitudinal turbulence intensity at 90th percentile, defined as the mean *'I'* value plus 1.28x standard deviation of the turbulence intensity at hub-height (three-dimensional) wind speed $\overline{U}$ of 15 m/s, '*a*' is a dimensionless slope parameter (Ref. Table 1) and $\overline{U}$ is the magnitude of the three-dimensional wind speed at the hub-height averaged over ten minutes. From IEC 61400-2, $I_{15} = 0.18$ and a=2. So, Equation (3) can be reduced to:

$$\boldsymbol{\sigma_{u,90pc} = 0.9 + 12\overline{U}} \qquad \text{Equation 4}$$

Equation (4) can be rearranged in terms of longitudinal turbulence intensity, I_u, as follows:

$$\boldsymbol{I_u = \frac{0.9}{\overline{U}} + 0.12} \qquad \text{Equation 5}$$

Equation (3) was proposed by Stork et al. [25] and is based on the assumptions of open terrain and hub-height wind speed ranging from 10-25 m/s. The IEC 61400-2 designates a maximum I_u of 18% for siting a SWT, however many built environment installation sites have registered the longitudinal turbulence intensity values well above the NTM parameters, as high as 30% in Nasu Denki Tekko Co. Ltd. report, and this has been attributed by researchers to the high concentration of roughness elements in the area [34, 61]. Evans et al. [62] looked into wind data at two urban locations and found that the turbulence intensities at the turbine's design wind speed of 7.5 m/s were 34% and 29%. When compared with the NTM, the turbulence intensities at both the sites were above 18%. In contrast, Hossain et al. [63] have reported that the turbulence intensity remained at or below the IEC level in open terrain. The assumed value of turbulence intensity, I_{15}, and slope parameter, 'a', to be used in Eq. 3 appears to be invalid for the wind conditions in the built environment. Recent studies on wind conditions in different built environment sites have also shown that the NTM underestimates both the magnitude and rate of change of wind fluctuations, σ_u, with increasing wind speed [24, 62]. In turbulence, highly intermittent statistics are found and this effect is even stronger in atmospheric flows [64-66]. Wind turbines should be able to withstand both stochastic turbulence and intermittent flow which result in fatigue and transient loadings on the turbine, respectively.

Using high resolution measurements, Carpman et al. [61] found out that the NTM in IEC 61400-2 underestimates the turbulence intensity in complex environments. Similarly, Murdoch University researchers have shown that the spectra from measured data in the built environment are not consistent with IEC spectra. Tabrizi *et al.* [24] studied the extent to which the IEC 61400-2 spectral functions are valid for the small wind turbines installed in urban settings. They investigated whether the von Karman and Kaimal spectra, as presented in IEC 61400-2, are appropriate for the use in the design of SWTs installed in the built environment and compared the turbulent spectra from actual flow conditions. They considered wind data at 4 different hub heights and 2 different atmospheric conditions (neutral and slightly unstable), used the misfit function [67] to quantify the discrepancies between the measured data and the model predictions. The authors observed that both the standard spectral functions underestimated, by a factor of 5 for the longitudinal wind component, and also underestimated the magnitude of the measured value for other two wind components. As a result, they proposed a corrected Kaimal spectral function for better agreement with measured values.

Considering the direct measurement of the wind resource, studies were carried out in regard to the effect of two key parameters on turbulence intensity - the data sampling rate and the averaging period. Although, IEC 61400-12-1 *Power performance measurements of electricity producing wind turbines,* suggests 10 minute averaging for large wind turbines and 1 minute for SWTs, Anderson *et al*. [68], Rotech *et al*. [69] and Tabrizi et al. [70] used different averaging periods and sampling rates to see their effect on measured turbulence in the built environment. They inferred that the choice of sampling rate did not influence the characteristic turbulent intensity, 'I_{15}' and power spectral densities (PSD). Changing the averaging period, however, affected the calculated values of turbulence intensity noticeably and thus the value of I_{15}. From the study of mean turbulence intensity in all three component of wind velocities, Tabrizi et al. [70] inferred that the longitudinal and the lateral components of the mean turbulent intensity were much more sensitive to changes in averaging period than that of the vertical component. They concluded that the conservative approach of 10Hz, 10-min averaging period gave upper estimates for the values of turbulence intensity and turbulent PSD.

From the literature, it has been evident that urban winds have higher measured turbulence intensity between 20%-30%, exceeding the NTM as mentioned in IEC 61400-2. This leads to increased fatigue loads and compromised performance which has implications for component reliability, maintenance, safety and overall turbine life [34]. Studies on the impact of high turbulence intensity on fatigue loading and power performance of SWTs in such elevated turbulent wind conditions reinforce the need for detailed assessment of urban wind flow fields, as discussed in following Sections.

5. Urban wind and intermittency

When it comes to interpreting the urban wind, it is imperative to gather and understand the required statistical information and spatial variability of the wind resource. Turbulence in wind flows in the ABL occurs due to the interaction between the ground surface and atmosphere [71]. The resulting incident flows on wind turbines can be highly turbulent, because these devices operate in the ABL and often in the wake of other wind turbines [58]. There is a shear stress between each successive layer of wind flow in the shear profile, giving rise to mechanical turbulence and the speed of the turbulent wind in the ABL varies randomly on different timescales. The short-term variations in wind (small-scale fluctuations) are superimposed on the mean wind velocity resulting in an intermittency of small scale turbulence that corresponds to an unexpected high probability of large velocity fluctuations [64]. Studies on wind turbulence also show that wind turbine control and power curves are also affected by wind fluctuation [72]. Understanding of such intermittent behaviour requires higher order statistical moments and can be quantified though incremental statistics i.e. probability density function of fluctuations.

As the response time of wind turbines is typically in the range of seconds, they are affected by the small-scale intermittent properties of turbulent wind and the intermittent nature of wind leads to high probabilities of extreme load changes on both torque and thrust [73]. This atmospheric turbulence imposes intermittent features on the whole wind energy conversion process and special attention is required to quantify the intermittence of wind power which may compromise the turbine's capacity for reliable generation. In the urban environment, the interaction of the atmospheric turbulent wind with urban structures reduces the scale of the turbulence and the dynamic response of small turbines may be affected if the length scale of the turbulence was comparable to the key length scale of the small wind turbine. To date, inflowing wind and turbine dynamics are not sufficiently characterized to model wind systems in the built environment, and this gap in the literature needs to be addressed.

To study the intermittency of turbulent wind, for instance, extreme events such as sudden gusts that cause transient loads on the turbine requires more detailed knowledge of the statistics of the turbulent wind fluctuations. While characterizing turbulent velocity field for the purpose of estimating dynamic loads, the probability density function of wind fluctuations is often expressed as a Gaussian distribution. Indeed, the NTM used in the IEC 61400-2 describes turbulence and turbulence intensity and assumes the wind fluctuations to have a Gaussian distribution.

While investigating wind dynamics, the difference between statistics of wind speed values and velocity increments must not be confused. The first-order ($\overline{U}$) and second-order (σ_u) one-point statistical moments of a velocity time series are summarized in the turbulence intensity (I) however; the value of turbulence intensity does not contain any dynamical or time-resolved information about the fluctuation field itself, i.e. it does not facilitate chronological and time-indexed trending of the wind speed observations [64, 74]. As a practical approach to wind field characterization, the first two statistical moments of the wind velocity time series are taken into account. The 10-minute mean value of the horizontal wind speed, $\overline{U} = \langle u(t) \rangle_{10\min}$, is used together with the standard deviation, σ_u, with respect to the same time interval Δt [73]. Equation 1 can be rewritten for velocity fluctuation as:

$$u'(t) = u(t) - \overline{U} \qquad \text{Equation 6}$$

To understand how wind gusts are related to small-scale turbulence, the statistics of velocity increments $\delta u_\tau(t)$ is required [64] where

$$\delta u_\tau(t) = u(t+\tau) - u(t) \qquad \text{Equation 7}$$

where τ is the time lag between the two fluctuations.

The fluctuation differences are naturally captured by the velocity increments. The wind speed increments characterize the variation of wind speed fluctuation '*u*' over a time scale, τ. The statistics of velocity increment is generally considered to analyse intermittency of small scale turbulence. The fluctuation differences are captured by the velocity increments. These increments are also directly related to loadings of wind turbines, their power output and damage statistics [75].

A probability density function (PDF) of the wind increments of the wind velocity or wind fluctuations $(\delta u_\tau(t))$ shows how frequent a certain increment value occurs and if this frequency depends on the time lag, τ. An intermittent PDF is characterized by heavy tails and a peak around the mean value differing from a Gaussian distribution. For the detailed characterization of wind fields, the PSD of horizontal wind speed is considered in the standard IEC61400-2. The Kaimal or von Karman spectra is normally used to describe the atmospheric turbulence and also to generate synthetic wind fields [76] however, these methods are limited to purely Gaussian statistics of the wind fields and do not take into account higher order two point correlations [77]. The turbulent wind has highly intermittent statistics and this can be seen in the PDFs, $P(\delta u_\tau)$, of the increments of the atmospheric velocity fluctuations during a time lag, τ.

As mentioned in IEC61400-2, wind turbines are designed to withstand the turbulent flow assuming the turbulence is a homogeneously Gaussian process. This situation has arisen partly due to convenience and partly due to limited understanding of turbulent wind flows [78]. The Gaussian assumption of oncoming wind is valid for boundary layer wind fields with homogeneous isotropic turbulence (HIT) associated with open terrains [43]. However, the purely Gaussian trend of wind fields as characterized by the IEC 61400-2 spectra is not reflected in measured data of built environment [76]. Particularly, the PDF for the longitudinal velocity increments, $P(u^{'})$, is related to turbulence. The turbulence in wind increments demonstrates highly intermittent statistics indicating a larger probability of the extreme events than that predicted by Gaussian [79] and this intermittent effect of turbulence is reflected in the deviation of the PDF from the Gaussian distribution [80].

Milan et al. [81] mention the occurrence of frequent gusts which are observed through heavy-tailed (more intermittent) statistics of the increment of the wind velocity. The occurrence of such gusts is related to probability of observing large increments and heavy-tailed form of the incremental PDF indicates more frequent extreme events than predicted by Gaussian PDF. Extreme events up to 20 standard deviations were recorded in some open terrain wind data. They state that these complex statistics cannot be reproduced using Gaussian wind field models and stressed the need for appropriate turbulence models. Similarly, Boettcher et al. [64] showed the measured PDF of the increments of their wind data was about 10^6 times higher than for a corresponding Gaussian distribution, meaning a certain gust event would occur much more frequently than what is expected through the current wind standard.

The statistics of wind velocity increments or changes within seconds characterize the temporal aspect of fluctuations whose non-Gaussian statistics are well known from small-scale turbulence [82]. The statistics of such wind velocity increment time series $\delta u_{\tau}(t)$ exhibiting non-Gaussian behaviour has been reported by Boettcher et al. [64], Morales et al. [83] and Leu et al. [66]. Numerous field data and lab tests [43, 64, 76, 83-85] have revealed non-Gaussian characteristics of wind speed increments in complex terrain but the literature is sparse on intermittency of the turbulent wind flow in urban areas and its effect on loadings of the turbine. Nielsen et al. [76] indicated the non-Gaussian behaviour of complex terrain wind conditions measured at different hub-heights having Skewness of -0.16, Kurtosis of 3.54 with Gaussian PDF severely underestimating the probability of extremely large as well as low events. Mücke *et al*. [16] explored whether the effect of intermittency in wind flows are passed on to wind turbine performance. The authors generated a non-Gaussian time series with excessive kurtosis– the statistics of generated velocity increments showing Gaussian behaviour at large time scale but large kurtosis at small scales indicating the influence of length scale on the turbine's dynamic loads. The authors found that non-Gaussian effects can increase the overall dynamic load during extreme events. They showed that the intermittent and gusty nature of wind leads to similarly intermittently changing torque on the turbine; the resulting torque showing larger fluctuations from atmospheric inflow than from standard Gaussian inflow, with the aerodynamic forces on the rotor shaft being transferred to the generator. Such fluctuations in the loads are not properly reflected by the IEC 61400-2 standard wind field models. Understanding when the deviation from Gaussian turbulence occurs and the impact of non-Gaussian winds on wind turbine performance and turbine loading are important for safety and reliability of wind turbine design [84]. The short-term fluctuation of wind and non-Gaussanity appear to have a high influence on wind systems and further investigation is required on the intermittency of turbulent inflow in urban areas.

Schottler et al. [86] experimentally studied the effect of intermittent and Gaussian inflow conditions on an instrumented model wind turbine in a wind tunnel using an active grid. Both flows exhibited nearly equal mean velocity values and turbulence intensities but strongly differed in their distribution of velocity increments at a variety of time scales. The intermittent inflow also showed a distinct heavy-tailed distribution of the velocity increments which was converted to similarly intermittent turbine data at different scales leading to intermittent loading. In search of advanced characterization, Mücke et al. [16] used higher order, two-point statistics to describe the turbulent structure of atmospheric wind fields more appropriately. The authors studied different inflowing wind fields on the rotor torque of a numeric wind turbine model and showed that intermittent wind leads to similar intermittently changing torques in the simulated wind turbine. They compared the measured atmospheric wind fields with the synthetic data generated from IEC Kaimal model and a continuous time random walk (CTRW) model. The CTRW model was used to reproduce the intermittent velocity increment distributions observed in atmospheric measurements. The results showed a large fluctuation in torque from atmospheric inflow compared to the Gaussian inflow, for instance, the value of 4σ corresponded to a torque increase of 88 kNm for 1.2 s; however, these differences were not visible with the rain flow counting method which is commonly used to count stress cycles of a signal to estimate fatigue and extreme loads on wind turbines.

Morales et al. [83] presented a statistical characterization of wind turbulence through one-point and two-point statistics using higher order moments. They proposed the use of PDFs of wind speed fluctuations and wind speed increments to grasp the statistical information of higher moments. Wächter et al. [79] used the intermittency parameter λ^2, previously used by Castaing [87], to characterize the wind speed increments and thereby describe and model empirical incremental PDFs. This proposed statistical parameter helped to comprehend the intermittent nature of the wind and the consequence of higher probabilities of extreme load changes.

The extent to which non-Gaussian wind statistics impacts WEC is an area of ongoing research. From the available literature, it is evident that the current wind standard for SWTs reflects Gaussian fluctuation whereas field data have demonstrated otherwise. The intermittent wind characteristics that are not accounted for in the current design standard can have a significant impact on wind turbines as intermittency in the wind flow fields has been found to be passed on to WT subsystems. Further, if the intermittent inflows lead to intermittent loading, and this is found to occur much more frequently than what the current wind standard predicts, there are implications in invoking this standard in designing WTs to withstand such wind conditions [86].

6. Influence of shape of buildings/roofs and siting locations on urban wind flows

Urban wind flows have been largely affected by various factors including the geometric detail of surrounding structures, the relative position of the turbine, terrain roughness, interacting airflows, local heat sources, wind shadowing, and street canyon effects. The influence of building configuration and shape of roof upon urban wind characteristics and performance of turbines have been discussed and investigated extensively by many researchers using numerical methods, as summarized in Table 2-4 or standalone rooftop HAWTs, standalone rooftop VAWTs, and diffuser augmented WTs and building augmented/integrated WTs. These numerical studies applied different turbulence models and several of them validated their results through experiments and wind tunnel tests to ensure the accuracy of the methods used. They have discussed the wind conditions in the built environment, particularly for the case of wind turbines installed on rooftops. These researchers have acknowledged the influence of the shape of buildings and urban orography upon the incoming wind profiles and shape of the roofs on the performance of roof mounted wind turbines.

Table 2 *Numerical studies on effect of roof profiles on potential standalone rooftop HAWT sites: isolated building*

Platform	**Configuration**	**Turbulence**	**Validation**	**Publication**

		Model		
ANSYS CFX and WAsP	3D RANS/ flat roof of a building	κ−ω SST[1]	Wind tunnel	Tabrizi et. al. [88]
ANSYS Fluent	3D Steady RANS/ building with different roof shapes	Realizable κ-ε + SIMPLE[2]	Wind tunnel	Abohela *et. al.* [89]
—	3D TRIZ/wind turbine on flat roof of a building	Standard κ-ε	Experimental	Padmanabhan [90]
OpenFOAM	Steady RANS/ solar panels mounted on a roof of a building	κ-ε, MMK[3], Modified Durbin	Wind tunnel	Silva *et. al.* [91]
OpenFOAM	3D Steady RANS/ wind flow around an isolated building	κ-ε (standard, Durbin, Durbin-New, Durbin Tominaga, MMK, RNG[4]), Non Linear κ-ε, κ−ω SST	Wind tunnel	Silva *et. al.* [92]
Fluent	2D Steady RANS/ wind flow around an isolated building for different wind turbines	—	No	Silva *et. al.* [93]
ANSYS Fluent	3D Steady RANS/ gabled roof	Standard κ-ε	No	Sari [94]

Table 3 *Numerical studies on effect of roof profiles on standalone rooftop mounted HAWTs: Identical buildings*

Platform	**Configuration**	**Turbulence Model**	**Validation**	**Publication**

ANSYS CFX	Steady RANS/buildings with patched roofs	Standard κ-ε	Wind tunnel	Heath *et. al.* [29]
—	LES/ uniformly staggered block array with different aspect ratio	—	No	Razak et. al. [95]
Fluent	3D Steady RANS/ wind energy between two perpendicular buildings	Standard κ-ε	Wind tunnel	Wang et.al. [96]
Commercial CFD code	3D Steady RANS/ influence of buildings on BIWT	Standard κ-ε	No	Chaudhry et. al. [97]
Fluent	3D RANS/ wind power in high rise building	Standard κ-ε	No	Lu et. al. [98]

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667 *Table 4 Studies on diffuser augmented/ building augmented turbines and VAWTs in the built*
668 *environment*

Platform	**Configuration**	**Turbulence Model**	**Validation**	**Publication**
diffuser augmented				
ANSYS CFX	2D/ steady RANS	κ−ω SST	wind tunnel	Kosasih et al. [99]
ANSYS CFX	3D/ steady RANS	SST	PIV and wind tunnel	Kulak, et al. [100]
ANSYS CFX/ BEM	RANS	SST	Wind tunnel	Kesby et al. [37]
ANSYS Fluent/ GAMBIT	3D RANS	Standard κ-ε	No	Wang, et al. [101]
ANSYS	3D RANS	modified κ−ω SST	Experimental model test	Jafari et al [102]
Building augmented				

—	3D URANS/ building+ turbine	κ−ω SST	No	Heo, et al. [103]
Savonius				
ANSYS Fluent	3D URANS / Building+turbine	Realizable κ-ε with SA vorticity based, SA[5] Strain based, κ−ω SST	experimental	Larin *et al*. [104]
ANSYS Fluent	2D Steady RANS/ rotor only	SA, standard κ-ε, realizable κ-ε, RNG κ-ε, κ−ω SST	experimental	Rogowski *et al.* [105]
ANSYS CFX	2D RANS / two designs of Savonius rotors	κ−ω SST	wind tunnel	Kacprzak *et al.* [106]
Star-CCM+	2D Non-linear URANS with SIMPLE	Realizable κ-ε	experimental	Zhou *et al.* [107]
OPAL+ Fluent	2D URANS /improved design of rotor with flat obstacle shielding the returning blade	Realizable κ-ε	No	Mohamed *et al.* [108]
ANSYS Fluent	3D URANS/ 2-bladed Savonius rotor	DES/ κ−ω SST	Experimental	Dobrev *et al.* [109]

[1] *SST Shear Stress Transport*

[2] *SIMPLE Semi-Implicit Method for Pressure-Linked Equations*

[3] *MMK Murakami–Mochida–Kondo*

[4] *RNG Re-Normalization Group*

[5] *Sparlart Allmaras (SA)*

These studies underpinned the fact that urban wind conditions vary significantly due to the influence of obstructions than that of open terrain and proper siting of the turbine is necessary for better energy yield. The CFD based study by Yang et al. [110] clearly showed the effect of the geometric details of the surrounding structures on the incoming wind flow field. They mentioned that the high-rise buildings in the upstream direction of their reference site tended to block the incoming wind and induced higher turbulence intensity over certain areas of the objective building. They suggested installing the micro turbines on the windward side of the buildings to acquire higher wind power production. Mertens [111] studied the energy yield of roof-top mounted SWTs for roof-top installation. He developed models to predict the flow features above the rooftop, calculate the average wind speed and the optimal hub-height for the installation of turbines. By providing example calculations, he showed methods of ascertaining the desirable hub-height above the roof, investigating the change of the undisturbed wind to the wind speed above the roof and the probability distribution of the wind speed above the roof.

Padmanabhan [90] and Sari [94] used CFD tools to evaluate the wind flow around a roof pitched at different angles and showed how the increase in wind velocity at the same height can be achieved by changing the slope of the roof. Padmanabhan [90] suggested using an adjustable pitched roof to increase the incoming flow velocity, with an speed up of 1.4x the reference velocity. Sari [94] used different angles for a pitched roof in a base house model to find out the maximum average wind velocity at a particular height. It was informed that for the same base house model height, a pitched roof of 30° had the best wind potential density. Abohela et al. [89] studied numerically the flow around the buildings and the influence of building shape on rooftop installed turbines by including both turbine and building in the same simulation. They studied six different types of roof profiles viz. flat, wedged/shed, gabled/pitched, pyramidal, barrel vaulted and domed/spherical, as shown in Figure 2. It was found that all the roof types had an accelerating effect on wind however the effects were different for different roofs. The authors concluded that the barrel vaulted roof was the most appropriate shape for roof-mounted wind turbine yielding 56% more electricity than a freestanding wind turbine in the same location under the same wind conditions. They also inferred that the best location of mounting SWTs is 30-50% of the building height above the building to avoid the effect of turbulence.

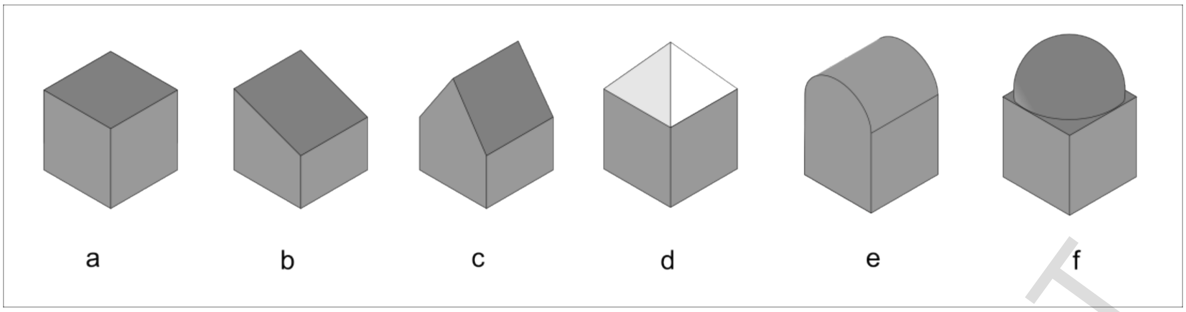

Figure 2 Schematic diagram of a. flat, b. wedged, c. gabled, d. pyramidal, e. barrel vaulted, and f. spherical roof shapes (Adapted from Abohela et al. [89])

Toja-Silva et al. [35] assessed numerically the wind flow around the sharp edged (Figure 2b wedged/shed) and curved roofs (Figure 2e barrel vaulted and Figure 2f spherical) on high-rise buildings (higher than 23-30 m) to identify the most adequate roof shapes that minimize the turbulence intensity and maximize the wind speed. They examined the effect of the different roof shapes on vertical profile of wind flow (U), turbulence intensity (I) and TKE (k). Compared with flat roof, they reported a moderate increase of turbulence intensity for the pitched roof (15.2%) and shed-roof (26.6%), while a moderate decrease for the vaulted roof (11.4%) and significant decrease for the spherical roof (40.5%). Comparing the turbulent kinetic energy, k, all shapes of roof reduced the value of k with respect to a flat roof, with the spherical roof showing the lowest 'k' value. Further, in line with what Abohela et al. [89] mentioned, the curved shaped roofs also generated a high wind profile concentration factor and concluded that both spherical and barrel vaulted roofs were the best options from energy exploitation point of view. Similarly, Yang et al. [110] suggested a rounded roof design produces lower turbulence intensity (<18%) and higher power density (as high as 86.5%) compared to typical rectangular roofs.

Razak *et al.* [95] reiterated the significant parameters of building profiles- layout (spacing) and geometry (height and width)- that influence the urban wind environment while Ledo *et al.* [112] conducted a numerical study of above-roof wind flow characteristics in three suburban landscapes characterized by housed with gabled, pyramidal and flat roofs. They concluded that wind flow characteristics are strongly dependent on the profile of roofs, with power density above a flat roof being greater and more consistent than that over a gabled or a pyramidal roof. Millward *et al.* [113] studied the variation of wind resource above the rooftop in the roughness surface layer (RSL) over a complex urban setting to identify the ideal rooftop location for turbine. They suggested mounting the turbine towards the leading edge of the roof with respect to the prevailing wind direction or installing the turbine at higher elevation if it is sited further from the leading edge to increase the available resource from the non-prevailing wind.

In addition to the HAWT research, several studies on the performance of building integrated WTs and Savonius wind turbines have been carried out using different numerical approaches. Larin *et al*. [104] investigated numerically the performance of a rooftop mounted conventional two-bladed Savonius type VAWT, concluding that no particular rooftop position improved the power coefficient (Cp) for such a turbine compared to a free stream turbine, however incremental increase in Cp from 0.15 to 0.24 was achieved by changing the number of blades to six or seven [104]. Zanforlin *et al.* [114] performed a 2D CFD study to verify if a convergent-divergent wall arranged as a diffuser over a Darrius turbine, placed closely parallel to the ridge of dual pitched roof, could be used to improve the concentration effect of the building. The authors discovered that a URANS (Unsteady Reynolds Averaged Navier-Stokes) approach was effective in predicting the improvement of 40-50% of power output with the use of diffuser-shaped wall. They mentioned that the same gain without the diffuser would require the turbine to be placed at least 1 m above the rooftop to experience higher wind velocities. The diffuser also decreased torque fluctuations on the turbine. Lu *et. al.* [98] mentioned that the increase in wind speed by 1.5-2x and wind power density by 3-8x can be achieved by utilizing the height and concentration effect of the buildings based on the local meteorological data and local high-rise building characteristics in Hong Kong. They too suggested modelling the annual wind flows over the buildings in the CFD tool to receive the highest potential wind energy resource and avoid turbulent areas. Rogowski et al. [105] studied the aerodynamic efficiency of a two-dimensional, two-bucket Savonius rotor by using CFD. They found a satisfactory comparison of numerical and experimental results and suggested that the CFD method can be used to optimize the shape of the buckets of the rotor. Zhou *et al.* [107] used a realizable κ-ε model to study the flow field and performance of conventional and batch-type rotors. This model was also chosen by Mohamed *et al*. [108] to evaluate the optimal blade shape of a Savonius rotor.

As can be seen from Tables 2-4, different authors have used different turbulence treatments and modelling approaches to examine the wind flow features around the built environment and its effect on the performance of wind turbines. From Table 3, the standard κ-ε turbulence model has been commonly used in analysing the effect of roof shape on SWTs mounted on a roof of a building set amongst identical buildings. Some of the simulation results were validated through comparison with experimental data and model tests and the authors claim the κ-ε model gives reasonably accurate results. Toja-Silva et. al. [91-93] conducted an extensive investigation on the accuracy of different turbulence models while simulating the wind flow around an isolated building with wind turbines and solar panels mounted on the rooftop. The simulation aimed to reproduce experimental measurements for both velocity and TKE on the building roof. Amongst the tested turbulence models, all linear κ-ε models showed better agreement with the experimental result (κ-ε Durbin model being more accurate) while the nonlinear κ-ε and κ−ω SST models overestimated the recirculation beyond the roof. Also, by analysing the behaviour of multidirectional wind flow around a building in urban area, they inferred that a HAWT performs better in open terrain while VAWTs have superior performance in high-density building environments. However, Yang et al. [110] argued that the realizable κ-ε model provided more reasonable predictions of turbulence intensity for simulations of the swirling and separating flows around buildings than those with the use of the standard κ-ε and RNG κ-ε models. Likewise, exploring the flow around a Savonius WT, Dobrev et al. [109] confirmed the capability of hybrid models such as Detached Eddy Simulation (DES)/ κ−ω SST or Large Eddy Simulation (LES) to produce more accurate results at the cost of significant computational time and resource.

In general, the objectives of these studies were to analyse the influence of shape of buildings/roof pitch on wind profile and to identify the best location for rooftop turbine in the prevailing turbulent wind conditions. Their focus was on the performance of the turbine rather than the available wind resource and interpreting the statistics of urban wind. Additionally, most of these studies were conducted numerically and the results were claimed to be fairly accurate to visualize the urban wind flow pattern around the buildings to decide on siting of the turbine. In the absence of experimental data and monitoring campaigns, these results could be relied upon to estimate the turbine's location, nevertheless, the choice of turbulence models and boundary conditions was mostly site specific and could not be generalized for similar studies. The application of CFD models is highly time consuming and resource intensive, particularly when one needs to model large areas with a domain of complex geometry to adequately access the impact of the structures on the wind flow [36]. Thus, it is crucial to have more experimental data that addresses the limitations of both CFD and wind tunnel tests and enhances the accuracy of the results.

7. Urban wind and power performance

Although the power output of a wind turbine largely depends on the average wind speed, it has been understood through recent studies that the power curve is influenced by both meteorological and topographical parameters. Wharton et al. [115] concluded that parameters such as atmospheric turbulence and wind shear are intrinsically related and influence the power output of a wind turbine. The wind turbine power performance standard, IEC 61400-12-1[116], defines the method for determining wind turbine power curves. SWTs. Operating outside the specified turbulence intensity as mentioned in IEC61400-2 can have an impact on SWT power production that is site-specific. The wind turbine power curve (WTPC) from IEC 61400-12-1 does not account for site varying turbulence and its impact on turbine power production [117]. Lydia et al. [118] and Trivellato et al. [119] have both noted that the IEC based power curves binned by wind speeds are unavoidably influenced by turbulence at the test site and cannot properly account for varying level of turbulence. Thus, the resulting power curve from the IEC will not be able to reflect the short-term fluctuations of power output induced by turbulent wind conditions or explain the orographic dependencies of a turbine's performance [120]. Noticeable discrepancies can be observed between the manufacture's curves and test results [121] and hence, the WTPC is required to be modelled considering the dynamic behaviour of the wind for better assessment and prediction of wind energy.

Power curves are constructed according to IEC 61400-12-1 [116] using wind-speed and power measurement. According to the standard, the wind speed samples are averaged at 10 minutes for large wind turbines and 1 minute for SWTs [122]. For characterization of atmospheric wind fields and turbulence, the horizontal wind speed over an observation period is binned by wind speed, over a time interval, in conjunction with standard deviation of wind speed over the same time interval [123]. Holling et al. et al. [123] notes that these quantities are one-point statistics and the current wind turbine power output measurements, particularly for SWTs, are based on an average wind speed over an observation period. This limits the information on the variability of wind within the period of observation when wind speeds are averaged this way [124]. Due to the non-linearity of wind power with wind speed especially near cut-in and rated wind speed, the procedure described in the IEC 61400-12-1 is sensitive to wind speed variations [125]. As a result, when mean wind speed data is used during the design and quantification of power and performance, it underrepresents the additional energy source carried by the wind during gusts and extreme turbulent events [40].

Quéval et al. [126] observed a lack of consistency while measuring the power curve of a standalone SWT using IEC 61400-12-1 and investigated the parameters that could be responsible for such variations, such as generator hearting, charge controller settings, anemometer position, generator inertia, battery voltage, and anemometer position. They made recommendations to improve the accuracy and consistency of the standard by including error bars with power curves, increasing the size of the usable database, rejecting system manual start data and installing the anemometer on a boom on the same tower as the wind turbine. Elliot et al.[127] supported the occurrence of systematic distortion of power curves as a result of errors in bins. The authors used the 1-minute averaging period for power curve measurement as recommended by IEC 61400-12-1 (H) for SWTs, and showed that this can lead to errors in annual energy production (AEP). Vermier et al. [122] suggested a technique to adjust the power curve based on a correction for the turbulence intensity, which was found to be strongly dependent on averaging period. They suggested averaging the long-term high frequency data so that the averaging time matched with the power curve. For low-frequency data, they proposed performing a short-term, high-frequency wind speed measurement to derive PSD function of the site.

The mean power as a function of mean wind is also strongly influenced by wind shear and wind veer, TKE, and dynamic response of the turbine to the wind [128]. Lubitz et. al. [117] inferred that increased ambient turbulence at lower wind speeds resulted in increased power but decreased energy production was observed at near-furling wind speed due to elevated turbulence. Pagnini et al. [129] studied the power output of two 20 kW SWTs (one HAWT and one VAWT) in an urban site. Their result showed that, for higher wind speeds, the measured power curves for both turbines were well below the rated power values, reaching a maximum of 13 kW which was lower than the rated power of 20 kW, and the power loss was attributed to high turbulence in the urban wind. The HAWT was strongly affected by gusts and large fluctuations of mean wind speed and direction, although its overall energy production was higher than that of VAWT. Similarly a study by Wagner et al. [130] based on turbines on flat terrain suggested a decrease in power output by 25% due to very high positive wind shear on flat terrain wind profile. Kosasih et al. [99] inferred from computational and experimental results that elevated turbulence levels in urban localities was the reason behind decreased performance of both bare micro wind turbines and diffuser augmented WTs at higher TSR. For the experiments, they generated turbulence intensities (2% to 29%) by the means of turbulence grids and assessed their performance in terms of power coefficient (Cp) and TSR. At lower turbulence, the diffuser augmented wind turbine exhibited a Cp of 0.22, about two times greater than that of the bare wind turbine with peak Cp of 0.15. At high TSR, the performance of both turbines decreased at increased turbulence intensity (Cp=0.07 for bare micro wind turbine and 0.15 for diffuser augmented micro wind turbine at TI=29%, from experimental results), yet the Cp of the diffuser augmented WT was still greater than that of bare WT indicating the potential in the addition of a diffuser for better performance at higher freestream turbulence. Hoe et al. [103] conducted a comprehensive CFD study on the performance of a 110 kW BIWT and compared its performance with a free stream turbine of the same capacity at a different reference wind speed and incoming flow angles. Results from the numerical analysis showed that the aerodynamic power output of the BIWT was higher than the turbine installed in the free stream due to the concentration effect caused by the accelerating wind between the buildings.

In more recent studies, Hedevang [128] suggested power production depends primarily on turbulence intensity and presented a new method for power curve estimation that accounts for some of the influence of turbulence intensity. The author developed a quasi-static model and a dynamic model to predict turbine power performance as a function of wind speed that estimated a power curve with the effects of turbulence subtracted. The ‘zero-turbulence’ power curve was in turn used to calculate the conventional power curve at any desired level of turbulence intensity. Similarly, Anahua et al. [131] presented a novel Markovian method to accurately characterized power performance of wind turbines independent of site-specific parameters. This method is based on the stochastic differential equations where the fluctuating wind turbine power output is decomposed into two functions: the relaxation function, which describes the deterministic dynamic response of the turbine to its desired operation state and the stochastic force function, which is an intrinsic feature of the wind power conversion system.

In summary, the studies focussing on the effect of turbulence and wind shear on power performance of wind turbines have shown disparate results and power curves are still conventionally presented as a function of hub-height wind speed alone, without information on wind velocity and turbulence intensity across the rotor disk [115]. Further, whilst such results show that ambient turbulence can either enhance or degrade the turbine's power production depending on the wind speed, the main concern is the cyclic loads and seemingly random gusting flows due to high turbulence that eventually impedes safe operation and cost investment during the planned lifetime of the turbine and this is explored further in Section 8.

8. Urban wind and dynamic loading

The importance in understanding wind turbulence for wind turbine engineering is clear; the stochastic and transient wind flows cause random, fluctuating loads and stresses over the whole structure, resulting in power fluctuations and reduced fatigue life of the wind turbine [56, 132]. The dynamic response of wind turbine structures to the imposed wind loads affects different components of a wind turbine including the rotor, power train and tower, and investigating the structural integrity of a wind turbine involves proper analyses of fatigue loading as well as extreme loading. Vasilis et. al. [57] claim that the elevated turbulence intensity of the wind flow was primarily responsible in reducing turbine structure fatigue life compared to other parameters such as the length scale of the turbulence, three dimensionality of the flow or yaw misalignment. Mouzakis et al. [133] introduced an analytical method to identify a parameter for fatigue loading of wind turbines. Their proposed methodology showed that turbulence in wind was the main fatigue causing parameter for all wind turbine components. The fatigue loading in complex terrain due to turbulent wind was as high as 30% compared to flat terrain operation. Other authors state that, in addition to elevated turbulence, sudden change in wind direction and extreme wind conditions like hurricanes, storms, etc. can lead to serious fatigue loading on the turbines. Such events adversely affect the blade's aerodynamic behaviour, turbine's performance and furling limits. Nijssen [134] concurred that during the operation of the turbine, the blade loading can be extreme due to a large number of load cycles in the structure's lifespan and the variability of load on rotor blades due to the stochastic nature of the wind.

Dimitrov et al. [135] concluded that high turbulent intensity can be linked to the fatigue failure of the turbines and the accumulated fatigue damage also increases with the turbulence. More specifically, high longitudinal turbulence intensity can have a detrimental effect on blade aerodynamic performance mostly due to stalled conditions occurring when the angle of attack changes because of sudden change in wind speed [136]. The effect of elevated turbulence levels in the built environment on turbine performance and fatigue loading have been studied by Evans et al. [62] through a detailed aeroelastic model of a 5 kW wind turbine developed in the FAST (Fatigue, Aerodynamics, Structures and Turbulence) code. They used input wind conditions from two urban locations and compared with the assumed wind conditions from IEC 61400-2. For the same mean wind speed of 7.5 m/s, their results showed increased mean turbine power due to elevated turbulence and a minor increase of 2% in rotor torque. More interestingly, the predicted damage equivalent load (DEL) for the turbine, assuming a nominal lifespan of 20 years, was 58% and 11% higher than the IEC 61400-2 scenario for the two built environment locations, respectively. Moreover, they also mentioned an increase of 55% and 18% in flapwise bending moments in those built environment sites compared to the simulated result from the IEC, which indicates a significant increase in blade loading. Similarly, Mouzakis et al. [133] showed a 30% increase of fatigue loading of wind turbines operating in complex terrain when compared to that in flat terrain.

A study by Lee et al. [46] indicated the strong influence of turbulent wind on extreme loading on turbines in a wind farm, where sites of higher terrain roughness led to increased damage equivalent loads. They also mentioned that atmospheric instability had marginal impact on the DELs and downstream turbines yielded higher DELs indicating that the turbulent wakes from the upstream turbines could have significant impact even at 7D separation distance. Thomsen et al. [137] suggested that fatigue loading of downstream wind turbines operating in the wake of an upstream wind turbine could be 5% to 15% higher when compared to that in free flow. Such fatigue loading parameters for the wind farm was ascribed to the increased turbulence intensity as well as reduced turbulence length scale. Rohatgi et al. [132] suggested that the most appropriate atmospheric conditions to operate rooftop wind turbines are either neutral or unstable states because the neutral atmosphere has the least wind shear and is best for the fatigue life of the rotor while the unstable atmosphere is more advantageous due to higher wind speeds.

Apart from discussing non-Gaussian behaviour in complex terrain, Nielsen et al. [77] presented new models for better load prediction capabilities of fatigue loading and extreme loading of wind turbines operating in a turbulent field. The fatigue loading process was a strongly non-linear function of the turbine loading and the authors show that the consequence of the fatigue loading imposed by non-Gaussian turbulence is a substantially higher fatigue compared to the Gaussian case. Amir et al. [138] compared the turbine blade load statistics for inflow turbulence fields of an open terrain standard Kaimal spectra with the measured turbulence spectra from the built environment. Their findings showed that the loading events had twice the magnitude of the loads as predicted by the standard spectra. The authors recommended the improvement of the standard to model the non-Gaussian wind statistics to address the design and safety concerns of SWTs in the built environment. The authors also suggested that small length scales and strong three dimensionality of the inflow are secondary factors behind increasing fatigue loads. Vasilis et al. [57] mentioned the significance of smaller length scales and three-dimensional flow of complex terrain wind conditions in increasing fatigue loads. They examined the impact of complex terrain wind conditions on the loading of wind turbines using computational means and found out the main fatigue driving mechanism is turbulence intensity.

Algarin [139] presented evidence of an increase in fatigue damage due to the effect of turbulence intensity on turbine fatigue loads. The turbulent nature of urban wind imposes complex and varying loads on turbine structures, affecting its performance and reducing its fatigue life. As fatigue damage is a major consideration when designing wind turbines, a reliable prediction of the fatigue life of wind turbine structures, particularly turbine rotor blades, is needed to provide efficient evaluation of turbine performance and service life by taking into accounts the loading and fatigue damage.

Studies so far have not precisely quoted the extent to which urban wind dynamics influence turbine parameters like fatigue loading, power, vibration, etc. This might be ascribed to key time scales and length scales which depend on the type of wind turbines, turbulence and rate of its dissipation. For turbulence which is not purely Gaussian, the smallest and fastest scales often exhibit extreme behaviour characterized by strong non-Gaussian statistics [140]. A fully developed turbulent flow is completely irregular and random and the turbulent eddies effectively transport both energy and matter over the time and length scales of varying sizes [61]. A scale-dependent analysis is necessary to capture the dynamics of turbulent structures and quantify the impact of turbulent wind on such SWTs.

9. Discussion

This literature review has revealed clear gaps that need further research in relation to siting SWTs in the built environment, as well as the current international wind standard pertaining to these SWTs, which must be addressed to ensure turbine reliability and predictable energy yield. One clear gap to be filled is the need of detailed resource assessment along with advanced characterization of turbulence through high frequency wind measurements in three-dimensions at multiple locations within built environments that can help accurate estimation of wind power production and also account for actual operating conditions. With field measurement for SWTs being uncommon, extrapolation of limited data and numerical simulations often fail to reflect actual wind conditions of such areas. The difference between predicted and observed wind energy production might be up to 40% due to turbulence effects, time interval of wind data measurement and extrapolation of the data from reference height to hub height [141]. Accurate quantification of urban wind fields and loading on the turbine components require detail data logging as well as instrumented SWTs in the urban areas. For instance, the University of Newcastle (UoN) at Callaghan, Australia has a fully instrumented 5 kW Aerogenesis machine along with a cup-anemometer to record the turbine hub-height wind conditions. The turbine is fitted with strain gauges and accelerometers to study the fatigue loading on the blades and other turbine components. The researchers at UoN have developed a detailed aeroelastic model of the turbine in FAST and compared its response to performance and loading with respect to the measured data [62]. Researchers at Murdoch University, Australia and University of Oldenburg, Germany are using ultrasonic anemometer to record wind data at higher sampling rates (10-40 Hz) and are conducting advanced characterization using higher order statistics. Such high-resolution data could also improve the computational models in replicating actual wind conditions. The use of onsite resource measurement combined with high-fidelity models can help understand the expected turbine production more accurately.

Another gap that requires further research is the need for comprehensive studies on turbulent statistics and characterization by numerical and experimental analyses, which will be indispensable to understand the complexity of turbulence at urban wind sites and quantify their effects on different aspects of wind energy conversion. Small-scale intermittent properties of atmospheric flows not only impact the wind energy conversion process and but also magnify loads on the turbines. This results in highly intermittent wind power output, not only transferring the intermittency to the grid but also amplifying it [142]. Such small-scale intermittency and its impact on wind energy conversion cannot be described alone by 10-minute mean value and standard deviation with respect to the same time scale as these are one point statistics. As atmospheric turbulence exhibits complex statistics properties especially in wind speed increment and fluctuation PDFs, use of advanced characterization with a 2-pt statistics including its higher order moments can help achieve more accurate prediction [73]. Recent works in stochastic analysis and characterization to grasp statistical properties of turbulence is mentioned Wächter, *et al.* [73] and the references therein.

Fields et al. [34] and Bussel et al. [143] have discussed a general evaluation and planning process related to technical evaluation, wind resource assessment, building characteristics and geometry, turbine technology, etc. for potential SWTs in the built environment. The upcoming report on a recommended practice for SWTs in the built environment developed by IEA Task 27, as mentioned previously, will provide the latest findings and suggestions regarding the design and operation of SWTs in the built environment and serve as a good reference to attune newer installations to urban wind fields. More importantly, the current wind standard, IEC61400-2, which is developed for the turbines to be installed in the open-field applications should undergo relevant revision to make it more inclusive of urban wind conditions. The existing wind field models in the standards contain a number of assumptions, including that the turbine will be installed in flat, open terrain. However, the same wind standard is applied for the turbines installed in the built environment. Such SWTs in non-open terrain experience wind conditions that lie outside the range of wind conditions modelled in the standards. Studies have also revealed that such urban sites are characterized by highly turbulent wind (I> 0.18) that can be linked to the turbine's structural fatigue. Murdoch University researchers like Tabrizi et al. [138] have investigated the extent to which the standard models, von Karman and Kaimal, used to simulate inflow for design load calculations, are applicable to such sites. They showed how different the IEC spectra currently used for the design of SWTs are from the actual inflow conditions experience by the rooftop installed turbines. As a result, they proposed an adapted Kaimal approach to modelling the turbulence power spectra for a rooftop site in the built environment by considering key parameters that influence shape and scale of the spectra.

Wind technology in urban frontiers is an active field of research with great potential. The advantage of exploiting wind energy in urban environment is distributed energy generation which offers significant benefits in terms of high energy efficiency, lower emissions, reduced energy dependence and stimulation of economy [35]. The niche of such small scale renewable technology in the built environment is evolving yet it is still less-mature than the large-scale or open-terrain wind systems due to many significant issues, as discussed above, remaining unaddressed for the effective integration of SWTs within the built environment.

10. Conclusion

This review has investigated the characteristics of wind in the urban environment, with a particular focus on the application of SWTs installed in such setting. In terms of understanding the inflow to wind turbines in urban environments, phenomena like the stochastic nature and the intermittency in urban wind flows are very important in terms of turbine functioning. Several studies have been carried out in characterizing the urban wind and identifying the extent to which currently used wind models are valid for built environment installations. These studies have identified key parameters such as hub-height, atmospheric stability and turbulent length scales that influence the behaviour of the turbines.

With respect to understanding the load and power performance of SWTs in the urban environment, the turbulence model of the local wind regime is a key factor in determining the energy yield and durability of the turbines operating within the influence of urban environments. The literature shows that the ambient turbulence can either enhance or degrade the turbine's power production depending on the wind speed. Some authors have reported a reduction in power performance, in the range of 25%-35%, which has been attributed to high turbulence intensity levels, greater than 18%. However, a comparative study on the performance of a bare SWT and a diffuser augmented SWT showed that the reduction in the power output with higher turbulence intensity may be offset to some extent by the addition of a diffuser.

In terms of the extent to which the current IEC 61400-2 design standard is valid for SWTs in the built environment, the normal wind condition turbulence models for use in aero-elastic codes do not appear to be valid for urban sites and the extreme wind condition models also do not capture the small-scale intermittency of urban wind flows. In particular, the turbulence models in the current wind standard are valid for flat, open terrain sites with expected wind speeds in the range of 10-25 m/s. Many reports have mentioned I_{15} between 20%-30% in the urban settings and that urban wind flow fields exhibits non-Gaussian characteristics with heavy-tailed PDFs. Such intermittent wind conditions are not accounted for in the current wind standard for SWTs and these complex statistics in built environment wind conditions need higher-order statistical moments to quantify and accurately characterize the urban wind inflows. The fatigue loading imposed by such non-Gaussian turbulence was also greater than that predicted by the standard spectra. A number of studies reviewed here revealed an increased fatigue loading of the wind turbines, as high as 30%, for a built-environment installed turbine and had about 58% higher DEL compared to one in the flat terrain, which is related to increased turbulence intensity.

Attempts have been made to interpret urban wind conditions to some extent in order to minimise or avert the effect of turbulence and maximize performance and durability. Through such studies, mostly based on numerical and stochastic modelling and a few by experimental and direct field measurements, issues related to power performance, suitable siting, and design optimization of turbine blades have been explored by researchers and developers. In the spirit of appropriate siting of rooftop mounted wind turbines in urban areas, the curved roof profile, barrel vaulted, or spherical shaped resulted in increased performance by more than 50% and reduced turbulence. It was suggested that mounting the SWTs at a height 50% above the building height can help minimize the influence of turbulence. Similarly, for the wedged or vaulted roof, the incoming wind velocity and power density can be increased by changing the roof pitch-angle for the same turbine hub-height. Such analyses were mostly done using the CFD codes and many authors have claimed that κ-ε turbulence model gave ~~the~~ fairly accurate results. However, such analyses were case-specific and experimental validations seem appropriate in such situations.

Further studies related to urban wind characterization through experiment and site data measurements are required to have more accurate knowledge of inflow turbulence, the effect of obstructions and urban wind profiles, occurrence of extreme events and issues related to dynamics loading of the turbine. This will assist in the design of turbines that have increased fatigue behaviour and predictable power performance when installed in urban areas. With the aid of these data, recommendations can be made for improvements to current IEC 61400-2 design standard for SWTs and expand the scope of the standard to include SWTs installed in the built environment sites.

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Highlights:

- current global status of SWTs technology and associated design standard IEC 61400-2
- rising application of SWTs in the built environment
- unreliable performance and structural integrity due to turbulent wind conditions and limited knowledge of urban wind characteristics
- elevated turbulence and intermittency in urban wind conditions, higher fatigue loading on SWTs
- current wind standard underestimating the urban wind conditions that does not cater to urban wind dynamics
- need of revision of wind standard to make it more appropriate for siting SWTs in urban areas