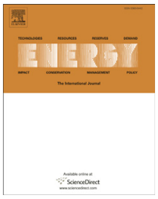
Energy xxx (2014) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



The progressive development of turbulence statistics and its impact on wind power predictability

T. Woolmington*, K. Sunderland, J. Blackledge, M. Conlon

School of Electrical and Electronic Engineering, Dublin Institute of Technology, Ireland

A R T I C L E I N F O

Article history:
Received 4 December 2013
Received in revised form
8 February 2014
Accepted 5 March 2014
Available online xxx

Keywords:
Turbulence
Wind power
Urban environment
Wind turbine

A B S T R A C T

Wind resource assessment is a critical parameter in a diverse range of considerations within the built environment. Engineers and scientists, engaging in building design, energy conservation/application and air-quality/air-pollution control measures, need to be cognisant of how the associated wind resource imposes increased complexities in their design and modelling processes. In this regard, the morphological heterogeneities within these environments, present significant challenges to quantifying the resource and its turbulent characteristics.

This paper presents three aspects of turbulence assessment within the built environment. Firstly, an analysis of how turbulence is currently quantified is considered. The industry standard, TI (Turbulence Intensity) is compared with a proposed alternative metric described as T_{Df} modelling (Turbulent Fourier Dimension). Secondly, the application of the turbulence assessment is considered with respect to how TI affects the productivity of small/micro wind turbines in complex environments though Gaussian distribution analysis. Finally, an extended discussion on current developments such as the concept of a turbulence rose and the ongoing development of statistical modelling is presented.

1. Introduction

The ability to harness kinetic energy from laminar wind flow is governed by an adjusted kinetic energy formula.

$$P = \frac{C_p \cdot \rho \cdot A \cdot u^3}{2} \tag{1}$$

where the mechanical output power (P) is a function of the performance coefficient of the turbine C_p, the density of air (ρ), the area swept by the turbine projected in the direction of the wind (A) and wind-speed (u).

In terms of wind energy conversion, the *Betz* limit, stipulates that the maximum possible conversion coefficient of a wind rotor is 59.3%. However, as a consequence of (aerofoil) blade roughness, wake effects, hub loss and tip losses system efficiency is significantly reduced resulting in efficiencies in the range of 30–35% [1]. It is also noted however that Betz Limit is wholly based on a laminar flow model and as such should not be used as a guide in turbulent environments. This poses significant problems for the industry, as the ability to quantify the wind resource in an urban environment accurately is currently questionable. Theories and mathematical models have been developed primarily from atmospheric climatology perspective and then subsequently adapted and amended to suit the wind industry [2].

CFD (Computational fluid dynamic) modelling, especially for aeronautical flows with turbulence models of the κ-ω type, are very popular and represent a wide-open area for research [3]. It is well known however, that CFD cannot reproduce physics that are not properly included in the formulation of the problem, which is the case in the study of turbulence [3]. In more recent years Davidson [4] highlighted the apparent split in current turbulent studies into two distinctive groups. On one hand applied mathematicians focus on the origin of turbulence in a deterministic approach to quantify turbulence characteristics. Engineers on the other hand tend to focus solely on the likely affects of turbulence on an application whether structural or a process based.

The wind energy market is predominantly based on large wind turbines that are situated in non turbulent rural and off shore environments, These environments offer optimal conditions for energy extraction and being sparsely populated, these locations can readily accommodate larger capacity turbines. The macro wind energy context has resulted in a cautious but questionable

---

* Corresponding author.
E-mail addresses: thomas.woolmington@dit.ie (T. Woolmington), keith.sunderland@dit.ie (K. Sunderland), jonathan.blackledge@dit.ie (J. Blackledge), michael.conlon@dit.ie (M. Conlon).

http://dx.doi.org/10.1016/j.energy.2014.03.015
0360-5442/

Please cite this article in press as: Woolmington T, et al., The progressive development of turbulence statistics and its impact on wind power predictability, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.015

approach when classifying turbulence and its likely effects in the boundary layer. TI (Turbulence Intensity) was proposed as a suitable means of quantify turbulence of dust particles based on a wind erosion model [5]. Following-on from this wind erosion model, studies on the statistical relevance as well as further empirical evidence were gathered. These studies ultimately led to a linking of the TI model to surface roughness parameters based on empirical experiments in wind tunnels [6]. Investigations linking TI and surface roughness tend to prioritise more thorough, a spatially distributed perspective on the time averaged mean and turbulent flow characteristics [7]. From wind engineering perspective, boundary layer physics has been employed to consider turbulence intensity with varying height within the boundary layer. Mertens [8] presented a model that scales TI in terms of the surface roughness length, z_0, but scaling in this regard is really only valid for wind energy systems located in rural environments.

There has been limited focus on the affects of power performance in the built environment where issues concerning planning and energy extraction in an associated turbulent wind resource present seemingly insurmountable challenges. From a resource evaluation perspective, site assesment using meteorlogical data has been shown to be a means of wind power prediction [9] while some researchers have employed proprietary software incorporating CFD [10]. The former requires specialised consideration in terms of the positioning of the metrological monitoring equipment, whereas the site specific nature of the latter means that an accurate and general means to assess the nature of the wind resource is difficult to establish. However, in the context of increased energy demand in cities, resulting from population migration [11] and the potential for smarter cities with smart network integration [12], there is an increased impetus for small wind energy systems in this regard. Currently nearly half of the world's population resides in cities and within two decades, it is envisaged this figure will rise to about 60% [11]. The need for demand centred generation with optimised transmission efficiencies creates the context for questioning what implications need to be addressed if wind generation technologies are to be optimally installed closer to urban centres.

From a wind energy system performance perspective, there is general acknowledgement that due to the rough and heterogeneous landscapes prevalent in urban environments that an increased level of turbulence will be manifested. It is also widely accepted that this increased level of turbulence will lead to a further degradation of turbine output. This paper will initially consider how this is not always the case, especially when quantifying turbulence by the current industrial standard TI (Turbulence Intensity). It also proposes that TI could be complimented by a further turbulence measurement T_{Df} to enhance the site wind statistics to a higher quality. This statistical indicator (T_{Df}) is compared to the classical TI indicator at two sites in Dublin Ireland. Following on from this the statistical effect of TI is examined in terms of power predictability estimation at the same two sites. The emphasis on the T_{Df} model is postulated through the authors' ongoing investigations in the development of artificial time series that will facilitate the representation of wind energy system inertia.

2. Quantification of turbulence

Increased prevalence of blind bluff bodies encountered in urban topographies escalates the erratic nature of wind velocities. This erraticism ultimately manifests an increased prevalence of turbulence, which has been shown to affect turbine performance both positively and negatively when measured using the TI (Turbulence Intensity) metric [13,14].

$$T.I. = \frac{\sigma_u}{\bar{u}} \tag{2}$$

where σ_u (ms^{-1}) is the standard deviation of wind speed over the sampling period (10 min) and $\bar{u}$ is the mean wind speed (ms^{-1}) over the sampling period.

However there are known limitations with the TI metric as a means to quantify turbulence in an urban environment. Firstly, the asymptotic nature of the metric as the mean wind speeds approach zero results in associated TI values that are greater than 100%. Gusts are also more prevalent in an urban context and as a consequence, the standard deviation can be uncharacteristically high. Secondly the TI metric was adopted into the wind energy industry as a means to classify site conditions on wind farms where wind characteristics are relatively laminar in nature (with an associated lower standard deviation). Another underlying principle on which the TI model is based is that wind speeds are considered to be normal (Gaussian) in nature within the industrial standard 10 min sampling period [15]. The authors have previously demonstrated that this not always the case and as an alternative proposed a methodology incorporating a dynamic Weibull PDF (Probability Density Function) [16]. This limitation of the NTM (Normal Turbulence Model) can be highlighted by considering a hypothetical but typical urban datum of a 10 min averaged wind speed of 2 m/s with a TI of 50%.

The (PDF) presented in Fig. 1 illustrates this limitation as all wind models are based on speeds rather than velocities (i.e. negative speeds should not exist). Note also, if these negative wind speeds are truncated the standard deviation and TI values will change.

That said, this currently does not present an issue for the following reasons. Firstly wind turbines have cut in wind speeds that are predominantly greater than 3 ms^{-1}. Therefore any power that is generated below a 10 min average wind speed of 3 ms^{-1} is negligible in respect to the yearly output for most sites. Secondly where these wind speeds are lower and more erratic, such as within the urban context, there are only a limited number of installations currently installed. The consequences therefore result in an inability to predict power performance accurately therein. This has led to the development of a new mathematical model for measuring turbulence called the Turbulent Fourier Dimension T_{Df} [17,18].

2.1. Field measurements

Observations are made at two sites in the Dublin city area using a CSAT3 three-dimensional sonic anemometer [19]. Measurements were taken consistently from 4/4/2012 to 15/5/2012 at both locations at a frequency of 10 Hz with an associated resolution-between $0.5 - 1.0\ mms^{-1}$, with data including date and timestamp and

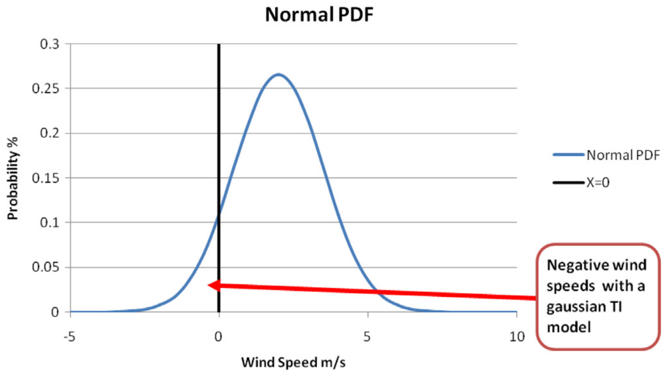


Fig. 1. Normal PDF with mean of 2 m/s and TI of 50%.

Please cite this article in press as: Woolmington T, et al., The progressive development of turbulence statistics and its impact on wind power predictability, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.015