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Urban wind: Characterisation of useful gust and energy capture

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ABSTRACT

Small-scale wind turbine operations within the urban environment are exposed to high levels of gusts and turbulence compared to flows over less rough surfaces. There is therefore a need for such systems to not only cope with, but to thrive under such fluctuating flow conditions. This paper addresses the potential importance of gust tracking technologies within the urban environment via the analysis of the additional energy present in the gusty wind resource using high resolution measurements at two urban roof-top locations. Results demonstrate significant additional energy present in the gusty wind resource at high temporal resolution. This energy is usually under-represented by the use of mean wind speeds in quantifying the power in the wind over longer averaging times. The results support the promise of capturing a portion of this extra energy through gust tracking solutions. The sensitivity of this "additional" wind energy to averaging time interval is also explored, providing useful information for the design of gust tracking or dynamic control algorithms for small-scale turbines. Relationships between turbulence intensity and excess energy available are drawn. Thus, an analytical model is proposed which may prove useful in predicting the excess energy available across wide areas from, for example, boundary layer turbulence models.

1. Introduction

Rising uncertainties over the future of oil and gas markets and increasing awareness of anthropogenic contributions to climate change have stimulated the quest for sustainable energy resources with lower CO_2 emissions than traditional fossil fuel sources. In 2008, the UK government set legally binding targets for achieving an 80% CO_2 reduction by 2050 compared to the 1990 baseline [1]. One attractive option for helping to achieve this target is increasing the usage of small-scale, decentralised and low-carbon energy sources, known as micro-generation. This would encourage energy generation close to the point of usage thereby reducing transmission losses. The UK government demonstrated its commitment to micro-generation with the introduction of the feed-in-tariff (FIT) system in 2010 [2]. The FIT system guarantees a fixed financial return for every kWh of renewable electricity generated. Investment in micro-generation has therefore become financially attractive, although only if income generated can outweigh initial installation and maintenance costs over the lifetime of the installation. The efficiency of the installation must therefore be optimal for the available local energy resource in order to maximise energy and financial returns.

Wind energy is currently enjoying the status of a commercially proven and cost effective technology with significant recent increases in annual global installed capacity [3,4]. The expansion of this industry into rural areas has occasionally been met with public disapproval. However, the smaller and quieter wind energy systems that have been developed for use in urban and rural areas may be less subject to these concerns. These small-scale wind turbines can easily blend into the city through either the incorporation of building mounted turbines in high rise city centres, or ground mounted turbines in semi-urban regions. This would lessen the losses experienced within the electricity supply system [5], as well as creating greater public awareness of renewable energy options. It is estimated that the installed capacity of micro/small-scale wind turbines in the UK could reach 1.3 GW by 2020 [6] if appropriate incentives and policies are put in place.

Urban and semi-urban wind environments are characterised by rapidly fluctuating, turbulent winds. This results from various factors including high surface roughness, the interaction between incoming flows and complex local building structures, and atmospheric instabilities caused by local heat sources [7]. The resulting complex, gusty urban wind rapidly changes in both magnitude and direction over a range of length and time-scales which may vary

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according to incoming wind direction and therefore upwind roughness characteristics. Roughness also strongly influences mean wind speeds and the urban surface is expected to slow down the mean wind close to the surface due to frictional and form drag effects [7]. These complex characteristics of urban wind resource have strong consequences on energy generation. McIntosh et al. [8] for example, highlighted the inability of rural-specific turbine rotor designs in tracking the high fluctuations inherent in the gusty urban wind resource. However, there exists a significant amount of energy stored within the higher frequency components of these gusts (as illustrated in the micrometeorological region in Fig. 1). Hence the possible extraction of this energy through advanced turbine controls may partially offset the penalty of wind turbines operating in the reduced mean wind speeds experienced close to urban surfaces.

Small-scale wind turbines fall into two major groups; Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). HAWT designs have been greatly developed over recent years, but are not necessarily fundamentally aerodynamically superior to VAWTs [10]. Their efficiency is highly dependent on wind direction (yawing). Small-scale HAWTs may suffer higher performance degradation in gustier (urban) operating environments due to yaw misalignment with a cos^2 dependence on the relative wind angle [11]. This can result in increased use of control power due to yaw corrections in rapidly fluctuating conditions, potentially decreasing the overall efficiency of the turbine system. VAWTs on the other hand have the ability to handle rapid changes in wind direction and operate at lower tip speed ratios, resulting in reduced noise emissions. VAWTs therefore seem a potentially good choice of configuration for the urban environment. However, they suffer from issues such narrower operating ranges (e.g. higher cut-in wind speeds than HAWTS), lower peak efficiencies and low starting torques. Many of these issues can be addressed through turbine controls [12,13]. However, designing effective controls relies on a detailed understanding of the nature of the available wind-resource in order to cope with rapid changes in wind speed and the generation of rapid torques changes [14].

High temporal resolution monitoring of wind speeds within urban regions is not widespread, potentially leading to higher levels of uncertainty in the assessment of wind turbine performance in urban areas [15]. Computational models of air flows over cities could potentially provide additional information on wind characteristics and may have the advantage of providing wide spatial coverage compared to a limited number of measurement sites [7,16]. Hence it is of interest to determine whether outputs from such models e.g. mean wind speeds and turbulence levels, could be used to assist in the prior assessment of turbine performance and in turbine system design. For this reason, this study focuses on the assessment of turbulence characteristics within urban areas and how measures of turbulence may be used to determine how much energy is available to a well-controlled turbine.

The primary objective of the work is the characterisation of typical urban wind resource based on high resolution anemometer measurements at two urban roof-top locations considered as potential turbine mounting sites. The additional energy resource available within high frequency gusts is quantified and is linked to standard measures of turbulence such as turbulence intensity. We highlight the effect of averaging time on the available wind power and demonstrate that the frequency of raw data must be well matched to potential turbine response times in order to make accurate assessments of the excess energy available to a particular turbine within gusts. By assessing the relationship between turbulence intensities and the excess energy available within a built environment, we propose an analytical model for predicting the excess energy and/or the total kinetic energy available at a potential turbine site. Section 2 introduces the concepts of gust tracking and gust efficiency and their importance to turbine operation. Section 3 presents methods for the characterisation of additional energy available within urban wind such as the gust energy coefficient (*GEC*), and excess energy content (*EEC*), along with a brief description of the selected urban sites for analysis and data processing methods. Section 4.1 presents results obtained from the two approaches in evaluating the additional energy available at these urban sites. The effects of averaging/turbine response time on potential turbine power output are discussed in Section 4.2. Here, relationships are drawn between turbulence intensity and excess energy content, and an analytical model for predicting *EEC* values within an urban environment is proposed. Finally the main conclusions are presented in Section 5.

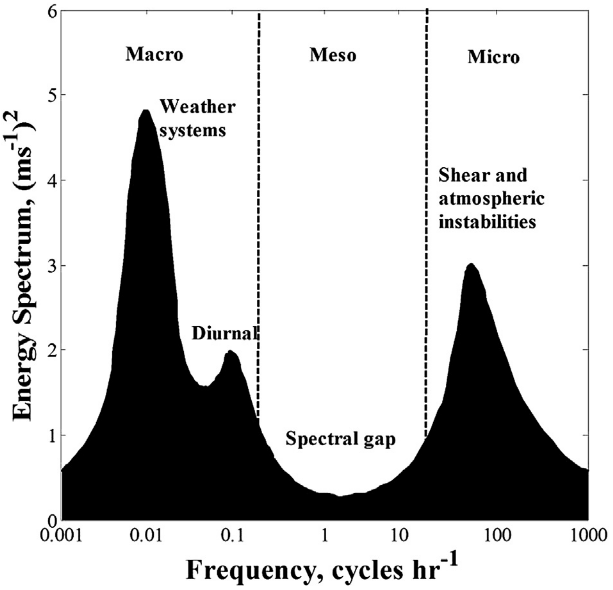

Fig. 1. Frequency distribution of fluctuating wind energy within the internal sub-layer, adapted from Van Der Hover [9].

2. Background

Gusts are defined as sudden fluctuations in wind speed which may contain within them wind speeds as high as 30–50% above the average [14]. An example of the gusty nature of real world urban wind speeds is illustrated in Fig. 2. It is shown that the wind speed varies greatly between 0.4 ms^{-1} and 14.5 ms^{-1} within a very short time period. Abrupt changes are experienced between points 1 and 2 (a jump in speed from 2.7 ms^{-1} to 13.2 ms^{-1} in $\leq$20 s) and points 3 and 4 (a jump from 2.8 ms^{-1} to 14.5 ms^{-1} in $\leq$40 s). These sudden rises and drops in wind speed, contrast with observations from coastal/open sea terrain [17] or rural terrain [18]. They result from increased turbulent drag caused by the high terrain roughness present within urban environments [19], rapid changes in flow direction around buildings/structures, and the formation of vortices [20] leading to regions of both flow acceleration and stagnation. These vortices can be influenced by various factors ranging from the effect of building area density to the substantial influence of roof heights and shapes on the flow structure within the urban environment [21]. All else being equal, Bertenyi et al. [22] suggest that a turbine system could experience a 60% loss or gain in power generation if relocated from a coastal/open sea site to an urban environment.