Energy for Sustainable Development 36 (2017) 44–54

Contents lists available at ScienceDirect

Energy for Sustainable Development

Performance characterisation of a commercial-scale wind turbine operating in an urban environment, using real data

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ARTICLE INFO

Article history:
Received 19 October 2016
Accepted 14 November 2016
Available online xxxx

Keywords:
Wind Turbine
Urban Environment
Economics
Renewable Energy
Annual Energy Output

ABSTRACT

Burgeoning demand for additional energy sources to supplement existing fossil fuel supplies has increased the requirement for efficient and cost-effective renewable energy. Wind energy is among the most prominent renewable sources and wind turbine technology has seen growth in recent years. Urban-sited wind turbines are a significant feature of this growth, with small-scale and roof-mounted turbines receiving attention in the literature. A detailed analysis of the performance of a commercial-scale wind turbine operating in an urban environment is critically important for furthering understanding of the viability of this technology in a non-traditional environment. This study provides a performance characterisation of an 850 kW-rated wind turbine situated on-campus at Dundalk Institute of Technology, Ireland, with measurements having been obtained over the course of one year. Characterisation of the wind conditions recorded at the wind turbine site has enabled development of a Weibull distribution model with shape and scale factors of 1.9151 and 6.9665 respectively. The power curve of the turbine in operation is presented for comparison with manufacturer specifications and utilised along with the wind speed data to calculate the wind turbine's annual energy output (AEO) for the year. Importantly, these findings can be used to assist with future wind energy developments in assessing the technical and economic viability using the approach outlined in this work.

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Introduction

As global energy demand continues to grow the ability of traditional sources of energy to satisfy this demand is receding (Soto and Jentsch, 2016). Renewable energy sources such as solar and wind power must be effectively promoted to share this energy burden. Wind energy is among the renewable sources with the greatest potential for clean and efficient power but further research is required to refine the performance of wind turbines, particularly in the urban environment. The Sustainable Energy Authority of Ireland expects 16% of all energy to come from renewable sources by 2020 in line with the 2009 Renewable Energy Directive (2009/28/EC) (S. E. A. of Ireland, 2016). Within this, the renewable contribution to gross electricity consumption is expected to be 40% by 2020. The production of electricity using wind energy could reduce reliance on oil while concurrently reducing carbon emissions (Shahida et al., 2016).

There are many examples in the literature of wind turbine performance characteristics having been validated through modelling (Bezrukovs et al., 2015; Pelletier et al., 2016; Gao et al., 2016). The majority of these studies contextualise the models within the framework of traditional wind resource sites, i.e. wind farms. However, study of the performance of wind turbine characteristics in the urban environment is much less prominent in the literature particularly with regards to on-site data collection and verification as opposed to behavioural modelling of turbine performance.

Although field tests can be relatively time consuming with a requirement for large datasets to be analysed (Wang, 2012), these criticisms of field testing in relation to aerodynamic performance can be considered virtuous for the type of analysis being presented here. For instance, the random variation in wind speed is an intrinsic characteristic of the location under examination and is therefore an important aspect of the wind turbine's performance (Shu et al., 2015).

Economic factors are a fundamental concern when assessing the commercial viability of any renewable energy source. Due to the distances from many turbine sites to urban environments where demand is highest, there is difficulty in integrating with existing power systems, thus increasing transmission costs and losses (Hoppock, 2010). An advantage of harnessing wind energy in urban environments is its proximity to the point of use. This factor offers improved energy efficiency, reduced energy dependence and overall reductions in greenhouse gases and other emissions (Toja-silva et al., 2013).

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http://dx.doi.org/10.1016/j.esd.2016.11.001
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Kanyako & Janajreh, 2015 have performed an economical study of a wind turbine under different wind conditions, stating that although wind energy like other renewables is capital intensive, although this is mitigated through factors such as fuel costs (Kanyako and Janajreh, 2015). The study cites Blanco, 2009 and states that capital costs including the wind turbine and grid connection can account for as much as 80% of the total project cost over its lifetime. However, electricity production and corresponding economic value is critically dependent on local wind conditions, making the site selection extremely important.

With regard to the economic and technological impact of wind energy technology in Ireland Flaherty et al. (2014) state that network costs are increased due to low population density which means more cable is required per consumer (84 m/customer in Ireland compared to 49 m/customer in the U.K.). This is one area where an on-site commercial-scale wind turbine in appropriate urban settings can provide relative benefits as the cost of transmission will be lower than it is for rural wind farm generated electricity. Furthermore, due to its unique geographical position in Europe, Ireland is well placed to harness its inherent wind, as well as ocean energy resources. However, to date there is little development towards integrating large-scale wind turbines within urban environments.

At present there is a trend in wind power generation for the use of wind turbines to provide supplementary domestic and commercial electricity supplies. One of the difficulties associated with these wind turbines is in determining locations within complex urban landscapes in which they may be viable. Urban siting of wind turbines has to date found greater presence in the literature with reference to small-scale and/or building mounted turbines (Sunderland et al., 2013; Shahizare et al., 2016). Detailed methodologies involving geometric data and aerodynamic performance of vastly differing surface areas is required to ascertain potential sites (Tomlin et al., 2013). In more suburban and residential areas with smaller buildings of similar heights, the majority of properties are unsuitable for these small turbines.

Traditionally, large-scale wind turbines have been almost exclusively located at high potential wind resource areas. This is particularly the case with commercial-scale wind turbines, which are established to take advantage of areas with optimum wind conditions (Karthikeyan et al., 2015). Substantial differences in terrain between traditional wind farm sites and a typical urban environment effect the wind characteristics (Ledo et al., 2011; Ricciardelli and Polimeno, 2006), and as a result the performance potential of a wind turbine. There are numerous examples in the literature of models used to describe the vertical distribution of wind speed in the urban environment (Lane et al., 2013; Li et al., 2010). However, a lack of data relating to surface and observed wind speeds means there has been a lack of validation of models in urban areas (Drew et al., 2013).

Performance models have been used to depict the predicted operational characteristics of various wind turbines (Wang, 2012; Yang et al., 2016; Karthikeya et al., 2016). This is an important feature in performance monitoring and in initial forecasting. Taslimi-renani et al., 2016 propose a new parametric model to characterise the wind turbine power curve based on the modified hyperbolic tangent (MHTan) (Taslimi-renani et al., 2016). Marvuglia & Messineo, 2012 present a machine-learning approach to modelling wind turbine behaviour (Marvuglia and Messineo, 2012). The results suggest that this non-parametric model provides fair performance when suitable pre-processing of the input data has been completed.

There is no question that the inherent potential in wind energy is great and a performance analysis of a commercial-scale wind turbine situated in an urban location has considerable value as a reference level for future projects attempting to incorporate this type of technology into populated environments. Through analysis of the wind profile in the area and its relation to the power output provided from the wind turbine a picture is developed to detail the actual on-site performance of the turbine relative to manufacture-stated performance. The effect of seasonal variation in wind speed profile is related to performance through a corresponding seasonal variation in power output and a detailed explanation of the wind turbine's performance, particularly in relation to power output, capacity factor and economic parameters will provide insight into the value of performance estimates and the future potential for this type of urban installation.

Methodology

The Vestas V52 HAWT being considered for this performance study is located on-campus at Dundalk Institute of Technology (DkIT), County Louth, Ireland (53°59′0.5928″N and 6°23′29.076″W). Upon completion of its installation in August 2005 the turbine was the first commercial-scale urban wind turbine in Ireland and the first on a college campus in the world.

The importance of the wind turbine's location cannot be overlooked when analysing its performance in generating electricity. As stated in the introduction to this paper, wind speeds are likely to be lower in urban environments, due to the more complex terrain and turbulence factors.

Figs. 1 and 2 show the site of the wind turbine under consideration. In Fig. 1, the image taken at 50m depicts the immediate area surrounding the wind turbine site which consists primarily of buildings on the college campus. Fig. 2, taken at 100 m shows the wider built-up area local to the turbine including a significant number of residential and commercial properties.

Fig. 3 is an image of the wind turbine at its location on the DkIT campus. Directly adjacent to the wind turbine are the campus buildings with many residential areas visible in the immediate vicinity. The town centre is at a distance of 2 km from the location of the wind turbine.

The data used for the performance analysis of the wind turbine was taken from measurements obtained at ten-minute intervals for the year beginning 1st January 2008. Wind speed and direction are measured on the wind turbine nacelle with values for power, pitch and turbine rotation speed also included in the data. The collected data has been processed and analysed using Matlab.

The data has been used to first perform analysis and characterisation of the wind conditions present at the site over a full year. The range of wind speeds recorded at the site, as well as direction and distribution are the key factors which have been considered. Importantly this information can be utilised for future wind turbine site analysis, particularly those on the east coast of Ireland with analogous proximity to urban landscapes.

The energy conversion performance of the wind turbine is analysed and discussed in relation to the local wind characteristics and its expected performance. The importance of this analysis is in determining the effect of this non-typical environment on the anticipated efficiency and operation of the turbine.

Local wind characteristics

Wind speed and direction

Fig. 4 displays each of the discrete wind measurements taken at ten-minute intervals during the year and exhibits the degree of fluctuation present in the wind. It is notable that there are significant fluctuations present throughout the course of the year, a factor which affects the turbine's ability to deliver a consistent power supply. As expected due to the local climate, peak wind speeds occur during the first three months of the year although it is notable that there are no incidences of the wind speed exceeding the wind turbine's rated cut-out speed of 25 m/s.

In Fig. 5, a wind rose derived from data obtained at the hub of the DkIT wind turbine in 2008 is presented. The wind rose contains details of the prevailing wind direction which is primarily emanating from a range of Westerly directions with a significant portion of wind blowing

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