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

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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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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


**Fig. 1.** The DkIT wind turbine site taken at a height of 50 m.

from a South-Westerly direction. Notably, there is a minimal wind presence coming from the North-East.

Additional information contained within the wind rose in Fig. 5 is the frequency of occurrence of different wind speeds denoted by corresponding colours along the radial direction. The most prominent ranges of wind speeds apparent in the wind rose are those between 4 and 10 m/s denoted by the blue and turquoise shaded sectors.

The data presented in Fig. 6 demonstrates the fluctuations in average wind speed throughout the year. The wind speeds for each of the twelve months of 2008 show an observable decrease in average speed for the summer months between May and September. Due to the cubic relationship between wind speed and power, those months displaying low average wind speeds are much less effective in providing substantial kinetic energy for conversion.

Table 1 contains information on the wind speed present at the DkIT campus site. The average wind speed of 6.19 m/s is consistent with the estimated yearly average of approximately 6.4 m/s based on initial feasibility work with the Irish Wind Atlas (Staudt, 2006).


**Fig. 2.** The DKIT wind turbine site taken at a height of 100 m.


**Fig. 3.** The DkIT wind turbine and surrounding urban environment.

*Distribution of wind*

A frequency distribution analysis was executed to enable further observation of the potential wind resource available at the site over the twelve month period. The resulting frequency distribution plot is presented in Fig. 7 where the recorded wind speed ranges from 0 to 21.3 m/s. It can be seen from the frequency distribution plot that the dominant wind speeds in the area occur within the range of 5–10 m/s.

The concentration of wind speed distribution within the range stated above has important implications for the performance characteristics of the wind turbine. Most notable is the fact that the vast majority of the wind speeds are distributed below the wind turbine's rated wind speed of 14 m/s. As a consequence the resulting generator output can only attain maximum power capacity of 850 kW for a relatively small fraction of the year.

It can also be observed from the frequency distribution plot in Fig. 7 that there is significant occurrence of wind speeds below the rated cut-in speed of 4 m/s. As the turbine cannot convert wind energy into electrical energy at these low wind speeds the associated time is effectively wasted with a corresponding depletion in overall power output and thus a reduction in the wind turbine's capacity factor (C.F.).

The Weibull distribution is often employed as a method of describing the density of wind speed (Sunderland et al., 2013; Usta, 2016; Ozay and Celiktas, 2016). The Weibull probability function is given by:

$$p(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \tag{1}$$

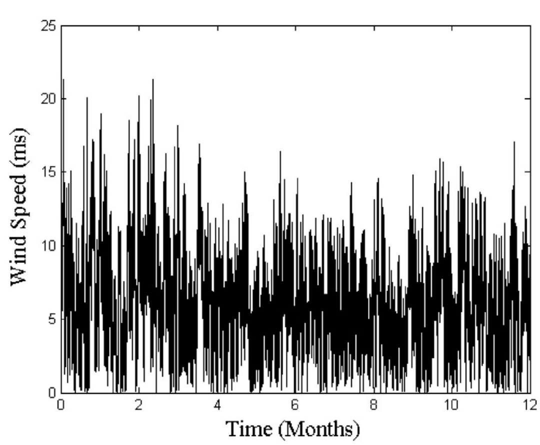


**Fig. 4.** Wind speed measurements taken from the DkIT wind turbine nacelle at discrete ten-minute intervals throughout the year.

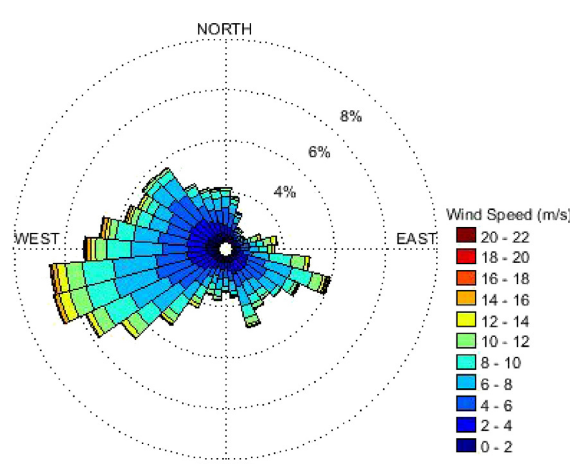


**Fig. 5.** Wind rose of measured wind speed and direction at the DkIT wind turbine site.

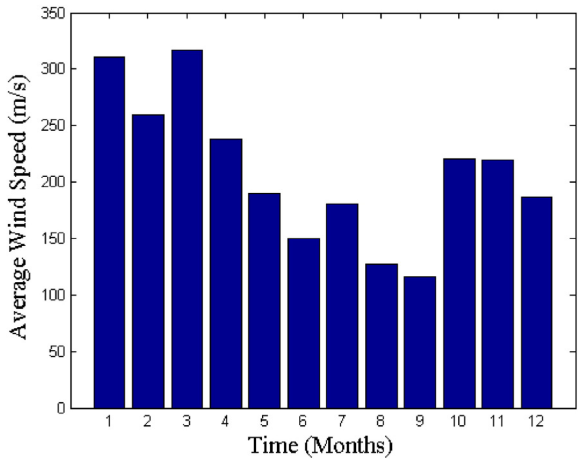


**Fig. 6.** Average wind speeds occurring at the wind turbine location for each month of the year.

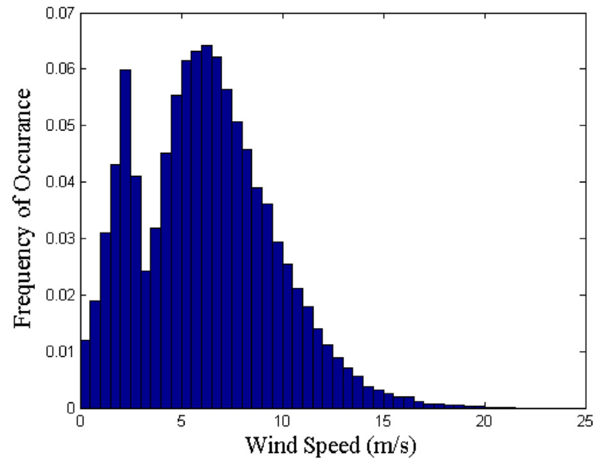


**Fig. 7.** Frequency distribution histogram representing the probability of each wind speed occurring at the DkIT wind turbine site.

where the parameters k and c are the shape and scale coefficients respectively and are calculated from the wind speed data plotted in Fig. 7. In order to estimate the shape and scale parameters of the Weibull distribution the Maximum Likelihood Method (MLM) is the most common method used (Vela, 2009; Karthikeya et al., 2016). The shape parameter, *k*, is calculated using the following equation:

$$k = \left( \frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_i^n \ln(v_i)}{n} \right)^{-1}. \tag{2}$$

Subsequently, an estimation of the scale parameter, *c*, can be calculated as follows:

$$c = \left( \frac{1}{n} \sum_{i=1}^{n} v_i^k \right)^{1/k}. \tag{3}$$

Fig. 8 shows the Weibull distribution of wind speeds for the measurements obtained. The Weibull curve uses the values calculated for *k* and *c* to model the probability of each of the wind speeds occurring at this site for this one-year period. The parameter values of k = 1.9151 and c = 6.9665 are applicable to future models for predicting the distribution of wind characteristics at similar sites to this one.

The Weibull distribution of wind speeds is also utilised to estimate the total occurrence of each wind speed throughout the year so that Annual Energy Output (AEO) and Capacity Factor can be predicted and compared with the measured data.

In an attempt to improve the predictive capability of the wind speed data, an investigation into the use of historical wind resource data within the scope of a Measure Correlate Predict (MCP) methodology was undertaken. This has become a popular method for the prediction of future wind characteristics at a target site on the basis of its correlation to a reference site (Weekes et al., 2015; Weekes and Tomlin, 2014; Carta et al., 2013). For the purposes of this study ten years of wind speed data up until the end of 2008 was obtained from a meteorological site at Dublin Airport (Met Éireann - The Irish Meteorological Service Online, 2016). Linear regression MCP was utilised to determine the correlation between the corresponding datasets for 2008 with the intention of using the historical data to predict longer-term wind speeds. When it can be established that there is a close relationship between the two sets of data (c. 0.8) then the reference data can be considered for future predictions.

Unfortunately, the data did not correlate well, having a correlation coefficient of only 0.35. The result of this was that the data obtained from Dublin airport could not be used as an accurate forecaster of future wind speeds at the DkIT wind turbine site. Several factors may have accounted for this including relative hub-height and distance from the coast. The geographical location of the meteorological site, at approximately 70 km from the DkIT wind turbine site, may also be a factor accounting for this negligible correlation.

**Table 1**
Wind statistics measured at the location of the DkIT wind turbine site.

| Mean | Std. dev. | Maximum | Minimum |
|---|---|---|---|
| 6.19 m/s | 3.32 m/s | 21.3 m/s | 0 m/s |

## Turbine performance characterisation

### *Power curve*

Analysis of the turbine's power conversion capabilities, particularly in a field test scenario with fluctuating wind conditions is important for enabling observation of the variation in power output in response to constantly changing wind conditions. The data can then be utilised for predicting the potential AEO of a wind turbine at similar sites, thus improving the accuracy of initial feasibility studies.

As this is a study into the real-world operation of the Vestas V-52 wind turbine it is essential that comparison is made with the manufacturer-stated power curve performance. In Fig. 9 the power

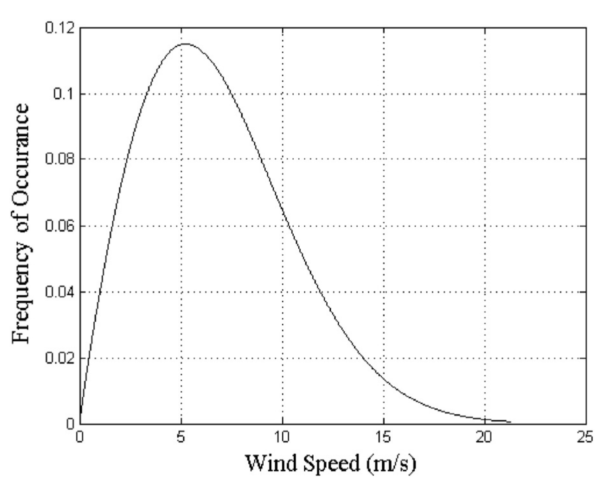


**Fig. 8.** Weibull distribution of wind speeds with shape, k, and scale, c, factors of 1.9151 and 6.9665 respectively.

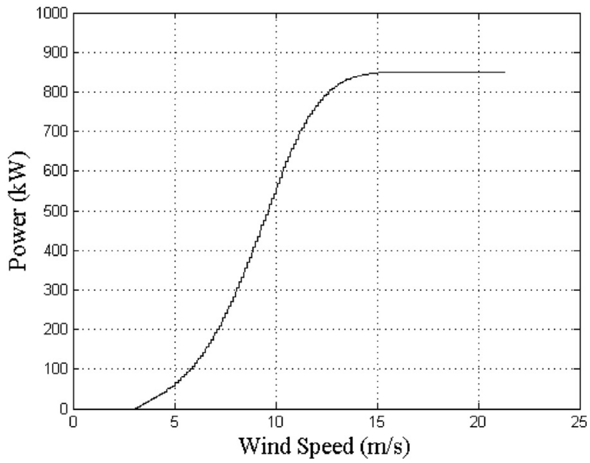


**Fig. 9.** Manufacturer-stated power curve for the Vestas V-52 wind turbine.

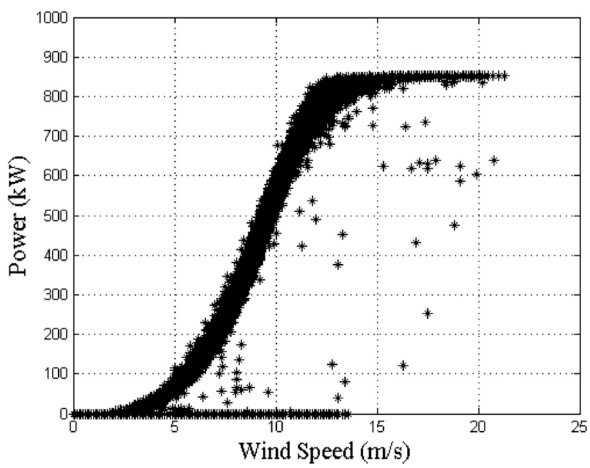


**Fig. 10.** Wind turbine power curve based on real measured data over a single year.

curve presented is representative of the manufacturer-stated performance of the wind turbine (Vestas Wind Systems, 2005). In Fig. 10 the power curve for the DkIT wind turbine is presented, having been determined in accordance with IEC 61400-12-1.

The power curve in Fig. 9 exhibits the predicted behaviour of the wind turbine, with peak-output power of 850 kW above the rated wind speed of 14m/s. In Fig. 10, the power curve data obtained from the wind turbine field-test resembles the expected performance as well as the typical contour of power curves presented in numerous studies (Lanzafame et al., 2015; Wang et al., 2016; Villanueva and Feijóo, 2016), although there are significant differences.

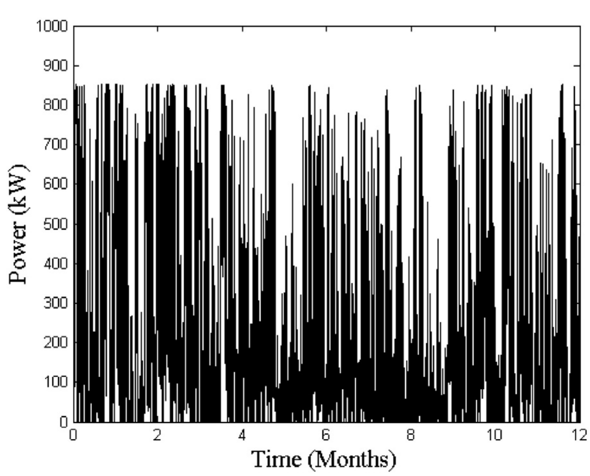


**Fig. 11.** Discrete power measurements taken from the DkIT wind turbine at ten-minute intervals throughout the year.

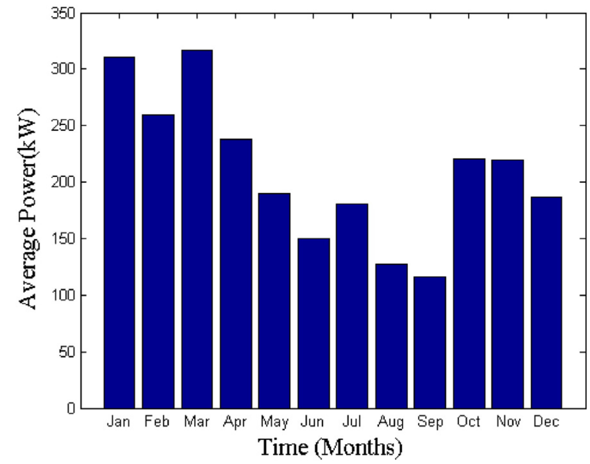


**Fig. 12.** Average power output from the 850 kW-rated wind turbine, located on the DKIT campus, for each month in the year.

The range of power outputs measured at different wind speeds is greater than the manufacture-stated performance and maximum power output, measured at 851.2 kW, is possible at wind speeds slightly slower than rated wind speed. There are also a number of outliers which are all positioned to the right of the body of the power curve, indicating that the wind turbine occasionally fails to output the power expected for a given wind speed.

The measured power curve data also presents several instances of the turbine outputting no power despite on-site wind speeds being above the rated cut-in value. This suggests that periods of wind turbine unavailability occurred during the year, a factor that affects its AEO performance.

Analysis of the wind turbine power curve would benefit greatly from the inclusion of data describing the turbulence intensity at the DkIT site. The complexity of the wind characteristics is certainly a contributing factor to the discrete power curve seen in Fig. 10. Unfortunately, turbulence intensity is not included in the dataset used for this study and may warrant future work on the subject.

Figs. 11 and 12 are distinct depictions of how the power output from the wind turbine varies throughout the year. In Fig. 11 each of the discrete measurements for power acquired at ten minute intervals has been plotted against time, displaying immense levels of fluctuation due to wind speed variation.

Fig. 12 shows the average power output for each of the twelve months. For those months exhibiting the lower average wind speeds discussed in the section Wind speed and direction, there is a prominent decrease in average power output. This is an expected consequence of the cubic relationship between wind speed and power, and demonstrates the importance of local wind characteristics in determining the AEO and economic performance of a wind turbine. The seasonal decrease in wind speed is a significant feature of the data but as the study considers a single year its predictive capacity is limited.

Table 2 contains information on the power output of the DkIT wind turbine. The average power of 209.73 kW is quite low in comparison

**Table 2**
Measured power statistics of the commercial-scale wind turbine located at the DkIT wind turbine site.

| Mean | Std. dev. | Maximum | Minimum |
|---|---|---|---|
| 209.73 kW | 240.01 kW | 851.2 kW | 0 kW |

with the wind turbines maximum power output of 851.2 kW, suggesting a capacity factor of approximately 25%.

*Power coefficient*

The power coefficient is an important parameter as it describes a wind turbine's aerodynamic efficiency in converting kinetic energy in the wind into electrical energy. Betz's limit places a theoretical maximum value of 0.59 on the power coefficient value associated with any wind turbine. Typical power coefficient values of 0.3–0.45 can be expected for a turbine operating in real conditions.

The equation used for calculating the power coefficient for each of the wind speed measurements is as follows:

$$C_P = \frac{P}{\frac{1}{2}.\rho.A.v^3} \tag{4}$$

where $P$ is the wind turbine power, $\rho$ is the fluid density, $A$ is the blade swept area and $v$ wind velocity. Values for power coefficient have been calculated for each of the measured wind speeds above 3m/s as this is the approximate cut-in speed obtained from the power curve in Fig. 10.

Fig. 13 displays typical behaviour of power coefficient against wind speed in relation to those present in the literature (Pelletier et al., 2016; Lanzafame et al., 2015), with efficiency peaking when wind speeds are between 7m/s and 10m/s. It is anticipated that power coefficient should drop off as wind speed approaches and exceeds the rated value for the Vestas V-52. At rated wind speed, the generator output will maintain a constant 850 kW, therefore efficiency decreases as wind speed increases.

*Tip-speed ratio*

Tip-speed ratio and its relationship with power coefficient is given a great deal of prominence in the literature as an indicator of wind turbine performance (Shahizare et al., 2016; Zanforlin and Letizia, 2015; Petković et al., 2013). Typically the tip-speed ratio is contained within the range of 2 to 12 as it has been for the plot in Fig. 14.

The tip-speed ratio is calculated using the following equation:

$$\lambda = \frac{\omega R}{v} \tag{5}$$

where $\omega$ is rotational speed (rads/s), $R$ is turbine radius (m/s) and $v$ is wind velocity.

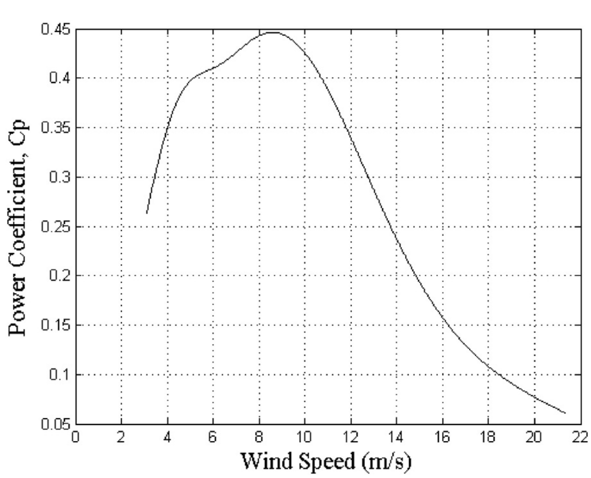


**Fig. 13.** Power coefficient, $C_p$ versus wind speed (m/s) for the 850 kW-rated wind turbine based on real data measured over a full calendar year.

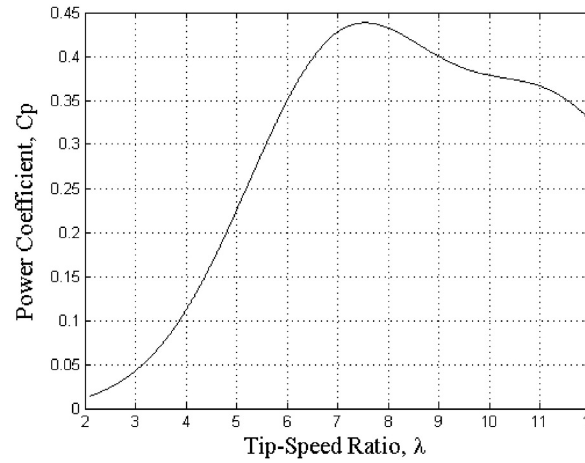


**Fig. 14.** Power coefficient, $C_p$ versus tip-speed ratio, $\lambda$ for the 850 kW-rated wind turbine based on real data measured over a full calendar year.

The $C_p/\lambda$ curve presented in Fig. 14 differs from many found in the literature (Petković et al., 2013; Ganjefar and Mohammadi, 2016) in that it exhibits a relatively slow drop-off of power coefficient post-peak. However, Jamieson, 2011 shows that a wind turbine operating close to optimal lift/drag ratio will exhibit this level of performance (Jamieson, 2011). The active pitch control system incorporated within the turbine accounts for this efficiency by changing the pitch angle of the rotor blades in response to current wind speeds and thus adjusting the power output.

Fig. 15 presents the $C_p/\lambda$ relationship for several different wind speed ranges, indicating how influential the wind conditions are on the operating performance of the wind turbine. This is an important factor in determining the selection of a wind turbine in relation to the particular characteristics of a given site-location. Clearly the DkIT wind turbine operates most efficiently in the wind speed range of 7–10 m/s, suggesting that the turbine is most suited to locations likely to exhibit high probabilities of this wind speed range. Predictably, the higher wind speeds, especially those greater than the rated speed for the wind turbine, result in the power coefficient being significantly diminished in comparison to the 7–10 m/s range.

*Pitch angle*

The Vestas V-52 features a system of microprocessors that control the pitching of the turbine blades. Figs. 16 and 17 show how the blade

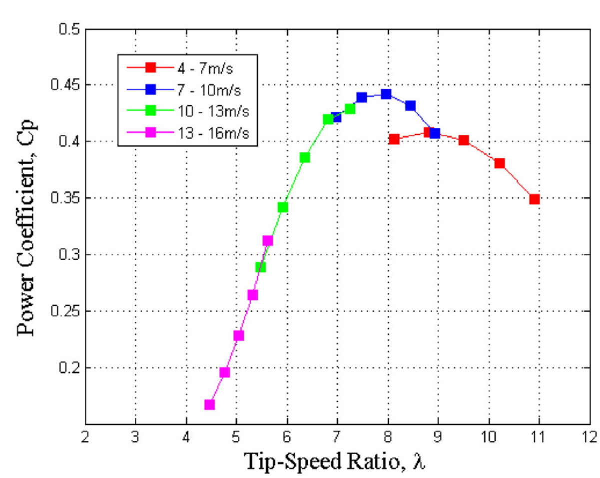


**Fig. 15.** Power coefficient, $C_p$ versus tip-speed ratio, $\lambda$ for the 850 kW-rated wind turbine for different wind speed ranges.

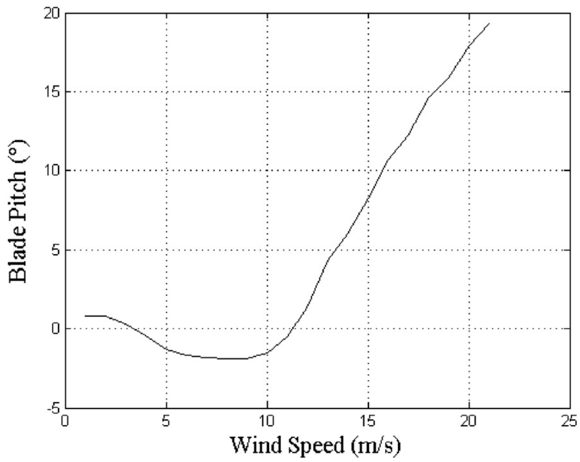


**Fig. 16.** Mode of blade pitch angles (°) for wind speeds between 0 m/s and 21.3 m/s.

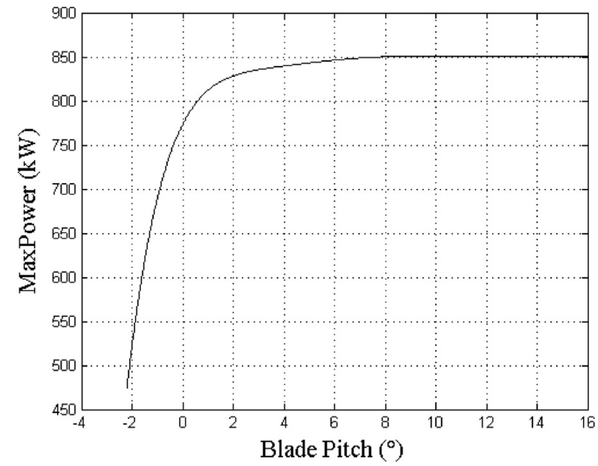


**Fig. 18.** Maximum power output for each blade pitch angle (°) between −2.2° and 16°.

pitch of the turbine under consideration for this study is adjusted in response to changing wind speeds. In Fig. 16 the mode of the pitch angles detected at each wind speed has been plotted to demonstrate the typical performance of the wind turbine's pitch control as it responds to varying wind speeds.

In Fig. 17 the data presented shows each of the pitch measurements obtained from the wind turbine over the course of the year, thus demonstrating its actual operation at the DkIT site. Much of the data is clustered to the bottom left of the plot where wind speed is below the rated cut-in threshold and pitch is not affecting the wind turbine's power output. Above the rated cut-in speed the pitch angle responds to changes in wind speed in the manner depicted in Fig. 17. Notably, the pitch angle rises significantly in response to wind speeds above 10 m/s.

The most significant finding from the wind turbine's pitch data is the presence of a large number of pitch angles in the region of 86.5° with no relation to wind speeds between rated cut-in and rated speed of the wind turbine. The data demonstrates the level of feathering required from the wind turbine throughout the year. Feathering may be employed as a means of halting the rotor during emergency shutdowns or when wind speeds have exceeded the rated level. However, the latter of these possibilities does not appear to be the case here.

Fig. 18 depicts the relationship between blade pitch and the maximum power output from the wind turbine. Just as increasing wind speed relates directly to an increase in blade pitch, a similar relationship between power output and pitch is expected. As the power output from the turbine steadily increases, rising towards 850 kW, the blade pitch is increased to control performance and maintain a consistent 850 kW output when wind speeds are above the rated speed.

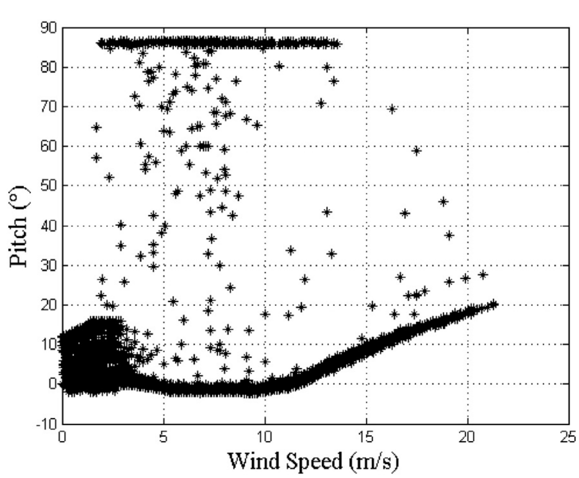


**Fig. 17.** Discrete blade pitch measurements for the DkIT wind turbine across the complete range of wind speeds recorded over one year.

## Wind Turbine energetic performance

### *Power curve analysis*

In order to estimate AEO from data contained in the power curve the average power at each wind speed has been multiplied by the Weibull distribution for the given wind speed and the number of hours in the year as follows:

$$AEO = 8760.\frac{1}{2}.\rho.A.\int_0^\infty C_p(\lambda)p(v)v^3dv. \tag{6}$$

The total AEO is calculated to be 2,368,831 kWh based on the power curve. The total energy converted by the wind turbine is used in the section Capacity factor to determine the capacity factor.

### *Measured data*

In order to calculate the total measured energy converted by the wind turbine, the sum total of the measured power acquired at ten-minute intervals was divided by the number of samples acquired to obtain an average power output. This value was then multiplied by the number of hours in a year to obtain the total energy outputted by the wind turbine. The measured output from the wind turbine was therefore 1,837,264 kWh.

The AEO resulting from the measured data is significantly less than the estimated AEO total based on the power curve, perhaps suggesting some unconsidered performance inefficiency or loss of availability in the turbine operation. The AEO values calculated and their corresponding capacity factors are available for comparison in Table 3.

**Table 3**
AEO and capacity factors of the DkIT wind turbine calculated on the basis of the measured parameters.

| | AEO (kWh) | C.F. (%) |
|---|---|---|
| Measured power data | 1,837,299 | 24.675 |
| Power curve data | 2,368,831 | 31.813 |

*Capacity Factor*

To supplement the data collected and the values calculated for the measured and estimated AEOs, a capacity factor has been calculated for each. The capacity factor is an effective and commonly-used metric of a wind turbine's overall performance and efficiency. As the data for this study has been collected over a one-year period the calculated capacity factors will reflect this.

Operating continuously at the rated wind speed the wind turbine could theoretically produce 7,446,000 kWh/year based on $AEO_{Theoretical} = 850$ kW x 8760hours/year.

The total maximum power can then be used to calculate capacity factor by dividing the AEO by $AEO_{Theoretical}$. The capacity factor is therefore calculated as:

$$C.F. = \frac{AEO}{AEO_{Theoretical}}. \tag{7}$$

Table 3 contains each of the AEO values, calculated and measured as well as their corresponding capacity factors. The capacity factor calculated for the measured power data is less than 25%. However, using the power curve data and the Weibull probability density for wind speed, results in a capacity factor of 31.813% for the wind turbine. This is a very promising value for an urban-sited wind turbine and indicates that the initial capital costs should be recuperated. It is also important to reiterate that the urban siting of the DkIT wind turbine places it in a position to minimise transmission losses, especially in relation to those wind farms in remote locations.

The capacity factor of the measured data and its contrast with those of the calculated AEO values raises the possibility of improvements in the operational efficiency of the DkIT wind turbine. The capacity factor of wind turbine sites can be increased with improved forecasting and siting techniques and the introduction of smart-grid technologies allowing greater amounts of electricity to be available to the grid (Blanco, 2009). These may be areas in which improved turbine performance can be pursued.

## Economic potential

*Net economic benefit*

Some of the data utilised for this economic benefit has been extracted from a 2006 study of the wind turbine's performance (Staudt, 2006). In 2006 DkIT consumed 3,000MWh of energy which was partially offset by the turbine outputting 1,435MWh. These figures, presented in Table 4, correspond to an electricity bill of €237,000 taking into consideration the wind turbine contribution and an approximate bill of €367,000 without considering the wind turbine's contribution. These figures are used to estimate the net economic benefit of the wind turbine for 2008 based on the AEO performance previously discussed.

An electricity price estimate of €0.123/kWh for 2008 has been obtained from a study into historical electricity prices in Ireland and Britain (Deane et al., 2013). Based on an assumed total consumption of 4,500 MWh the total electricity bill for 2008 is then estimated as €553,500.

The saving per kWh of energy converted by the wind turbine is calculated from the 2006 data at €0.091/kWh. Applying this value to the AEO calculated for the measured data in the section Capacity Factor results in €167,194. The savings credited to the wind turbine can then be subtracted from the total bill. These calculations result in an estimated electricity bill of €386,306.

Blanco, 2009 suggests that a reasonable estimation of Operation and Maintenance (O&M) costs lies between 0.01 and €0.02/kWh (Blanco, 2009). Assuming a value of €0.01/kWh the total O&M costs for 2008 are €18,373.

Export credit, the amount of money received for supplying electricity to the grid has been estimated at €27,000 for 2008. The net economic benefit of the turbine for the year 2008 is calculated by subtracting the O&M costs from the savings credited to the wind turbine before adding the value of exported electricity. The estimated total net benefit of the wind turbine in 2008 is €175,821.

The net benefit of €175,821 attributed to the wind turbine for 2008 is within the bounds of what is required for the turbine to recover capital costs within the initial estimated time-frame of seven years.

As the vast majority of the total expense of a wind turbine is expended on installation reducing O&M costs is one of the few measures available during the life of the wind turbine for reducing total cost. Al-Najjar and Hailemariam (2012) provide several procedures for improving the maintenance solutions surrounding wind turbines with the aim of improving overall economic performance.

*Present value*

The Net Present Value (NPV) method is a means of predicting the investment potential of a project in the medium-to-long-term. The NPV method takes account of the cash-flow related to the turbine and provides comparison with the initial capital investment. Cash benefits are discounted over time depending upon interest rates and the year in which the benefits arise (Kealy, 2013).

Both NPV and levelised cost of energy (LCOE) have been calculated for the wind turbine's life-cycle of twenty years based on a range of O&M cost predictions between €0.005/kWh and €0.02/kWh. O&M costs are the only variable in the calculation. A report by Oxera Consulting Ltd in 2011 presents an indicative range for the discount rates of onshore wind turbine projects of 7–10% (Oxera Consulting Ltd, 2011). For the results presented in Table 5 and Fig. 20 a discount rate of 8% has been selected. As the discount rate is held constant at 8% the PV of AEO remains constant at a value of €18,038,872.41.

Table 5 contains values for NPV and LCOE resulting from varying O&M costs and Fig. 19 presents the LCOE versus factors of O&M costs based around €0.01/kWh. The LCOE for the wind turbine based on an O&M rate of €0.01/kWh and a discount rate of 8% is €0.072/kWh which is in line with expectations for an on-shore wind turbine. Fig. 19 shows that the LCOE varies linearly as O&M costs are adjusted.

Table 6 contains data on the effect of discount rate on various parameters of the wind turbine's economic performance. Discount rates ranging from 7%–11% have been selected based on values suggested in the

**Table 4**
Economic assessment.

| | |
|---|---|
| AEO | 1,837,300 (kWh) |
| DKIT consumption (estimate) | 4,500,000 (kWh) |
| Electricity price (estimate) | €0.141/kWh |
| Turbine savings (estimate) | €0.091/kWh |
| Bill (w/o turbine) | €634,500 |
| Bill (w/turbine) | €476,306 |
| Savings (Gross) | €167,194 |
| O&M costs (€0.01/kWh) | €18,373 |
| Export credit (estimate) | €27,000 |
| Net benefit | €175,821 |

**Table 5**
NPV and LCOE of the DkIT wind turbine based on variation to O&M costs.

| O&M costs | 9,186.5 (€0.005/kWh) | 18,373 (€0.01/kWh) | 27,559.5 (€0.015/kWh) | 36,746 (€0.02/kWh) |
|---|---|---|---|---|
| O&M (PV) | €90,194 | €180,389 | €270,583 | €360,778 |
| NPV | €689,434 | €599,239 | €509,045 | €418,851 |
| LCOE | €0.067/kWh | €0.072/kWh | €0.077/kWh | €0.082/kwh |

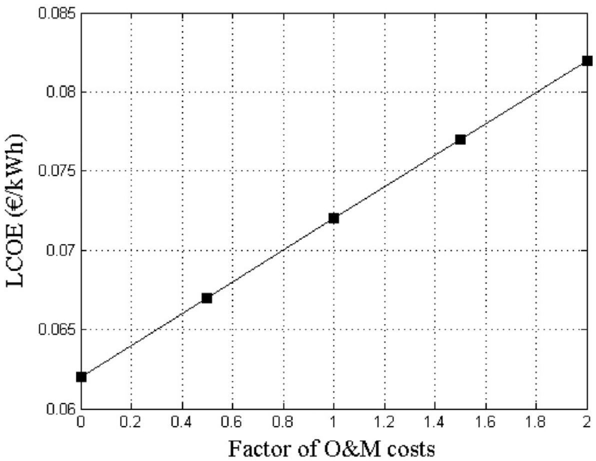


**Fig. 19.** The effect of O&M costs on LCOE based on a discount rate of 8% and an initial estimate for O&M costs of €0.01/kWh.

**Table 6**
NPV and LCOE based on a range of discount rates between 7% and 11%

| | 7% | 9% | 10% | 11% |
|---|---|---|---|---|
| O&M (PV) | €194,644 | €167,719 | €156,420 | €146,310 |
| AEO (PV) | 19,464,372 | 16,771,867 | 15,641,962 | 14,631,014 |
| NPV | €735,653 | €477,993 | €369,866 | €273,123 |
| LCOE | €0.068/kWh | €0.077/kWh | €0.082/kWh | €0.087/kWh |

Oxera report (Oxera Consulting Ltd, 2011). However, results dependent on a discount rate of 8% have been omitted from Table 6 as they can be seen in Table 5. The initial rate of O&M costs have been held constant at €0.01/kWh (€18,373) for this analysis.

Fig. 20 displays the effect of varying discount rates on the wind turbine's LCOE as it rises in line with an increased discount rate.

The economic analysis presented in this section demonstrates the impact of the economic parameters such as discount rate and O&M costs, on the wind turbines economic performance. At the highest discount rate indicated in the Oxera report cited (Oxera Consulting Ltd, 2011), the wind turbine exhibits a LCOE value of €0.087/kWh. Although this is quite high for an onshore wind turbine it can be viewed as an upper limit of the expected performance. A LCOE in the range of €0.072/kWh to €0.082/kWh is expected.

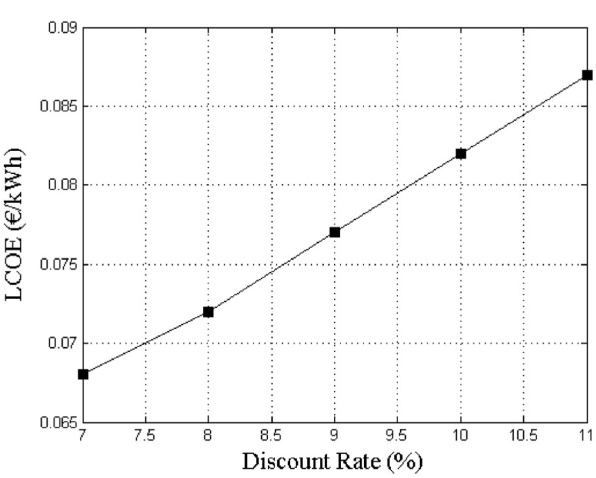


**Fig. 20.** The effect of a varying discount rate on the LCOE of a commercial-scale wind turbine.

## Conclusions

In this paper a comprehensive study on the performance of a large-scale commercial wind turbine located in an urban environment is presented. An analysis of the local wind characteristics has been carried out with a wind rose depicting the direction and intensity of local wind conditions over a one-year period. A Weibull distribution of wind speeds is presented and utilised to develop predictions of potential AEO values for the wind turbine. This Weibull distribution is an important indicator for future wind conditions at this location and other similar sites. The calculation using actual on-site wind characteristics resulted in values of 1.9151 and 6.9665 for the shape and scale factors respectively. These values may be utilised for predicting the wind speed conditions of sites similar to the DKIT campus. Furthermore, the information may assist in modelling the potential performance of a future installation as well as its AEO.

Technical characteristics of the wind turbine's performance are presented and demonstrate that it operates within the range expected. The measured power curve correlates well with the manufacturer's published power curve with a peak output of 851.2 kW and a mean power output of 209.73 kW. The monthly power output of the wind turbine shows how power output levels deteriorate seasonally with decreasing wind speeds. At sites with relatively low mean wind speed, the seasonal effects are a significant factor in reducing the turbine's AEO.

The wind turbine power curve presented in the study provides valuable contrast with the manufacturer-stated performance. Although the wind turbine's power curve closely matches the expected trend, there are several outliers and instances of zero output in the data which show how real-world operation can differ from modelling and testing. The data presented on the wind turbines $C_p/\lambda$ relationship at different wind speeds supplements the power curve data as a means of determining the likely performance of the wind turbine at a specific location.

The economic study of the wind turbine has estimated a NPV of €18m and a LCOE of €0.07/kWh, putting it in the range expected for this type of wind turbine and making it economically competitive in relation to comparative renewable energy technologies.

The inability of the research team to utilise the MCP methodology places some limitation on the accuracy of the economic analysis being posited in this study but does not render it unworthy of consideration. Further research is required to obtain a useful dataset for the purposes stated and enable a more comprehensive prediction of the economic and energetic performance of the DkIT wind turbine.

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