Using meteorological wind data to estimate turbine generation output: a sensitivity analysis

M. L. Kubik[1,*], P. J. Coker [2], C. Hunt[3]

[1] Technologies for Sustainable Built Environments, University of Reading, United Kingdom
[2] School of Construction Management and Engineering, University of Reading, United Kingdom
[3] AES, Richmond upon Thames, United Kingdom
* Corresponding author. Tel: +44 (0)118 378 4670, E-mail: m.kubik@pgr.reading.ac.uk

Abstract: Various studies investigating the future impacts of integrating high levels of renewable energy make use of historical meteorological (met) station data to produce estimates of future generation. Hourly means of 10m horizontal wind are extrapolated to a standard turbine hub height using the wind profile power or log law and used to simulate the hypothetical power output of a turbine at that location; repeating this procedure using many viable locations can produce a picture of future electricity generation. However, the estimate of hub height wind speed is dependent on the choice of the wind shear exponent α or the roughness length z_0, and requires a number of simplifying assumptions. This paper investigates the sensitivity of this estimation on generation output using a case study of a met station in West Freugh, Scotland. The results show that the choice of wind shear exponent is a particularly sensitive parameter which can lead to significant variation of estimated hub height wind speed and hence estimated future generation potential of a region.

Keywords: *Wind shear exponent, Wind profile, Renewable energy, Variability, Intermittency*

Nomenclature

α	*wind shear coefficient* .... *dimless*	k	*von Karman constant*.......................*dimless*
u_1	*horizontal velocity component at* z_1 .....ms^{-1}	z_0	*surface roughness factor* ....*m*
u_2	*horizontal velocity component at* z_2 .....ms^{-1}	z_1	*vertical measurement height 1* ....*m*
u_*	*friction velocity*....................................ms^{-1}	z_2	*vertical measurement height 2* ....*m*

1. Introduction

Various influential studies investigating the impacts of the variability of renewable resources begin with meteorological (met) station data, as this is often readily available over a wide geographic area [1-3]. Alternative studies instead rely on statistical methods, e.g. [4], have direct access to wind farm generation data, e.g. [5], or take a black box approach and consider the impact of wind at a system level, based upon industry forecasts and policy targets, e.g. [6].

A typical weather station will log hourly mean horizontal wind and gust speeds at a standard height of 10m, which may be extrapolated to estimate the wind speed at a standard wind turbine height. By applying a wind turbine power curve, the wind speed can be converted into a hypothetical generation output, and repeating this process to a greater number of turbines and to a wider geographical area can give insight into how a future involving a high penetration of renewable energy may look.

Two common analytical models are used to map the wind velocity profile with height, and hence allow the calculation of horizontal wind speed at a certain elevation over the earth's surface: the log law and the power law [7]. In reality, the complex and dynamic nature of the atmospheric boundary layer means that one single profile will not provide a consistently reliable extrapolation of wind speed from one height to another. The variables in the log and power laws therefore are particularly important to consider when performing the kind of future resource study suggested above. This paper investigates precisely this sensitivity by carrying out a resource analysis of hourly mean wind data for a met station in West Freugh, Scotland, in the same manner that other influential resource studies [1-3] have used.

First, the relevant background literature and the methodology used in this research are presented, with particular focus given to the assumptions made in the analysis. The findings of the research are then discussed, the implications identified, and avenues for future research are highlighted.

2. Background literature

There are two main analytical models used to extrapolate wind speeds to greater heights: the log law and the power law. In general, the two models have been shown to perform equivalently in shear extrapolation predictions on average, although at any particular site one model may be better than another [8]. However, for either approach, large errors in the predictions are common and this error is exacerbated further when energy production is estimated. This section introduces the theory and assumptions behind these two approaches, and indicates some of the previous work into better understanding and applying them.

2.1. The Logarithmic Law

The log law's origins lie in boundary layer fluid mechanics and atmospheric research [7]. For determining the horizontal velocity u at a height z is commonly expressed

$$u(z) = \left(\frac{u_*}{k}\right)\ln\left(\frac{z}{z_0}\right) \tag{1}$$

Where u_* is the friction velocity, *k* is the von Karman constant and z_0 is a measure of surface roughness known as the roughness length; u_* and *k* are generally determined from a graph of experimental data [9].

There are cases where wind velocity u_1 is known at a reference height z_1, and required at another z_2, in which case it can be derived from equation 1 that

$$u_2 = u_1 \frac{\ln(z_2) - \ln(z_1)}{\ln(z_1) - \ln(z_0)} \tag{2}$$

This is a simpler expression to solve, as it eliminates the need to calculate the friction velocity and von Karman constant, which can be difficult to estimate in the atmosphere. A neutral wind profile is assumed [9], where convection is negligible, the lapse rate (the fall of temperature in the troposphere with height) is nearly adiabatic and stratification is nearly hydrostatically neutral (i.e. there is no *vertical* wind flow in the atmosphere without excitation).

Seasonal variations in local terrain characteristics can have a profound influence the on estimation of z_0 (due to changes in foliation, vegetation, snow cover etc.). Table 1 extracts some guideline roughness lengths for different types of terrain as given in the European Wind Atlas [10].

Table 1- Typical Surface Roughness Lengths z_0

Terrain	z_0 (m)
Water areas (lakes, fjords, open sea)	0.0001
Airport runway areas	0.01
Airport areas with buildings and trees	0.02
Farmland with very few buildings and trees	0.03
Farmland with closed appearance	0.10
City	1.00

2.2. *The Power Law*

The power law [9] is an empirical equation, expressed

$$u_2 = u_1 \left(\frac{z_2}{z_1} \right)^{\alpha} \tag{3}$$

Where α is the wind shear coefficient or power exponent, an empirically derived constant applied over the height range that the power law is applied. Calculating the wind shear coefficient becomes trivial if the wind speeds at two heights are known, as equation 3 may be rearranged in terms of α

$$\alpha = \frac{\ln(u_2) - \ln(u_1)}{\ln(z_2) - \ln(z_1)} \tag{4}$$

The exponent α is a dynamic value that is dependent upon the stability of the atmosphere. The wind shear exponent may be taken as constant for a given height in a given height range, but a different α should be chosen depending on the height range over which the power law is applied [9]. For neutral stability conditions, α is approximately 1/7, or 0.143 (this rule of thumb is known as the "1/7$^{\text{ths}}$ power law"), regarded as a reasonable but conservative estimate [11]. However, various site specific studies have found that the coefficient is actually greater, and that this leads to underestimation of the energy resource available [12-14].

2.3. *Usage of the two laws*

Each method requires knowledge of a wind speed at a reference height, and one further coefficient: a roughness length z_0 in the case of the log law and a wind shear coefficient α in the case of the power law. Both may be calculated using on site measurements, but the power law is common engineering practice [15] favoured by the wind industry and consultants, as the wind shear coefficient is a dynamic value that varies according to a large number of factors including time of day, season, atmospheric stability and regional topography [11]. The log law on the other hand is only valid under certain assumptions regarding atmospheric stability, and actual profiles may deviate from the log law. In the wind industry the two methods are generally checked where possible to ensure that they provide similar results [15].

Unlike wind developers, many researchers do not have the resources to conduct field investigations (for example, by erecting weather masts) to determine the horizontal wind characteristics at likely development sites, and instead rely upon available 10m met station data and shear profile extrapolation for their models, often over a large height range and assuming one constant annual value.

3. Methodology

Meteorological data for this study was obtained from the British Atmospheric Data Centre MIDAS database for a station located at West Freugh airfield, Scotland. A wider number of sites were considered, but this site was chosen because it provided a reliable and continuous data set. Five years (2005-2009) of Hourly Climate Messages (HCM) were chosen over Synoptic (SYNOP) data for analysis, as the latter relies on a 10min wind sample to produce an hourly average. HCM readings sample continuously to produce an hourly average mean wind at a standard height of 10m. The readings were recorded to the nearest knot, but converted to SI units for analysis.

The literature identified that the log and power law extrapolations were each dependent on a single parameter: the surface roughness z_0 and the wind shear coefficient α respectively. Four surface roughness lengths were selected for analysis using Table 1, based upon an understanding of the site topography (i.e. an airfield with building and trees being the best description, and hence the starting point) and similarly, a range of four shear coefficients were also selected, using the $1/7^{th}$ power law as a starting point. Both sets of parameters were selected to represent a realistic spread of values that an analyst might take for the site [15].

A Vestas V80 2MW wind turbine power curve was used for calculation of generation output, with an assumed hub height of 60m. The generation outputs were calculated each year for each of the extrapolated profiles of 10m wind speed, producing an apparent indication of the site's annual capacity factor, energy production, zero generation hours and the proportion of time when a hypothetical turbine would be producing no power output.

4. Results

Annual capacity factors, based upon wind speed extrapolation to 60m, are shown in Figure 1, with all other results summarised in Table 2. A sample week (from June 2005) has been extracted from the analysis and used to illustrate the change in estimated 60m wind speed and generation outputs under each law; this is shown in Figure 2.

Figure 3 maps the profile of wind speed with height from a starting height of z_1=10m, using the log and power law with the variables specified in the methodology. A typical wind speed of u_1=5ms^{-1} was a chosen to illustrate this behaviour. The extrapolated wind speeds at z=60m are emphasised for discussion, as this was the height of interest in this study.

Table 2 - Summary of mean values attained under log and power law

5 year average	power law (α)				log law (z_0)			
	0.100	0.143	0.200	0.300	0.010	0.020	0.030	0.100
Capacity Factor	0.266	0.307	0.364	0.463	0.293	0.306	0.314	0.348
Zero prod hrs	1777	1779	1785	1468	1778	1779	1779	1782
% non gen time	20.4%	20.4%	20.5%	16.9%	20.4%	20.4%	20.4%	20.5%
Total GWh	4.623	5.348	6.344	8.057	5.105	5.320	5.470	6.053

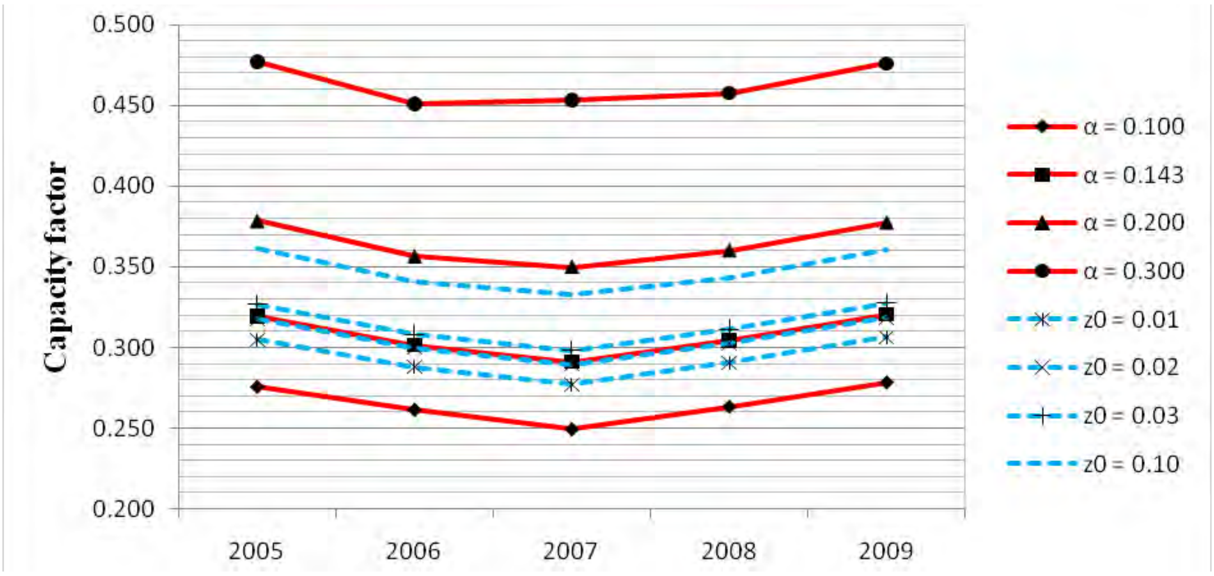
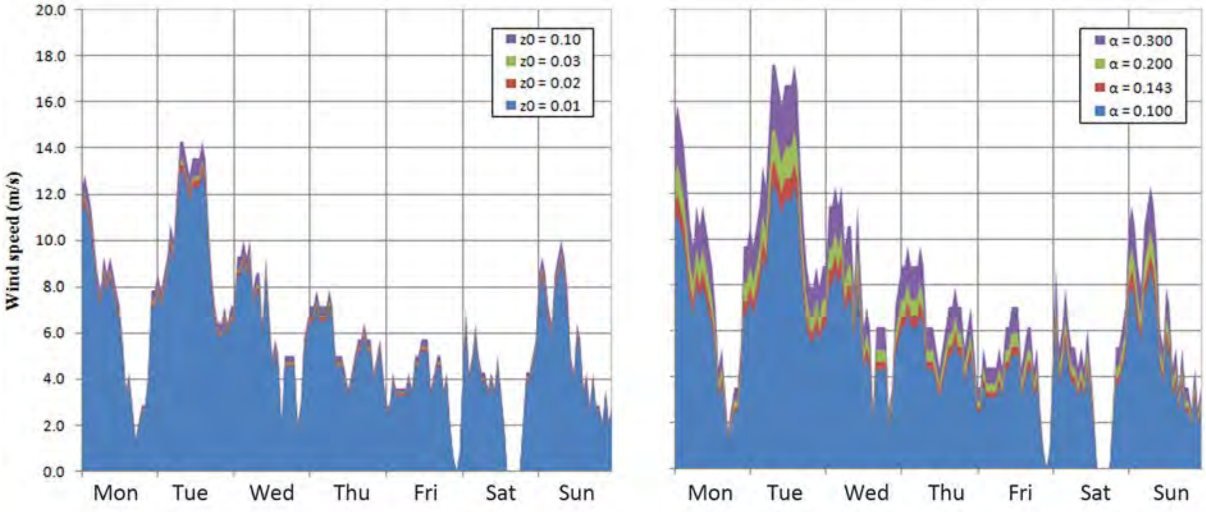
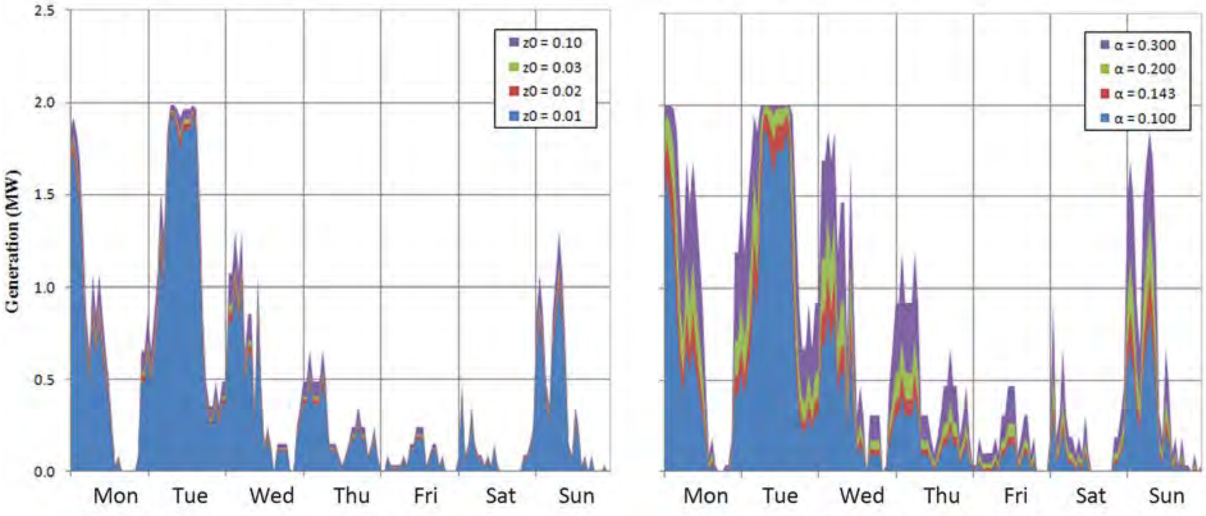


Figure 1 - Graph of extrapolated annual capacity factors



(a) Extrapolated wind speed (log law) *(b) Extrapolated wind speed (power law)*



(c) Generation (log law) *(d) Generation (power law)*

Figure 2 - Sample week of wind extrapolation and estimated generation using the log and power law

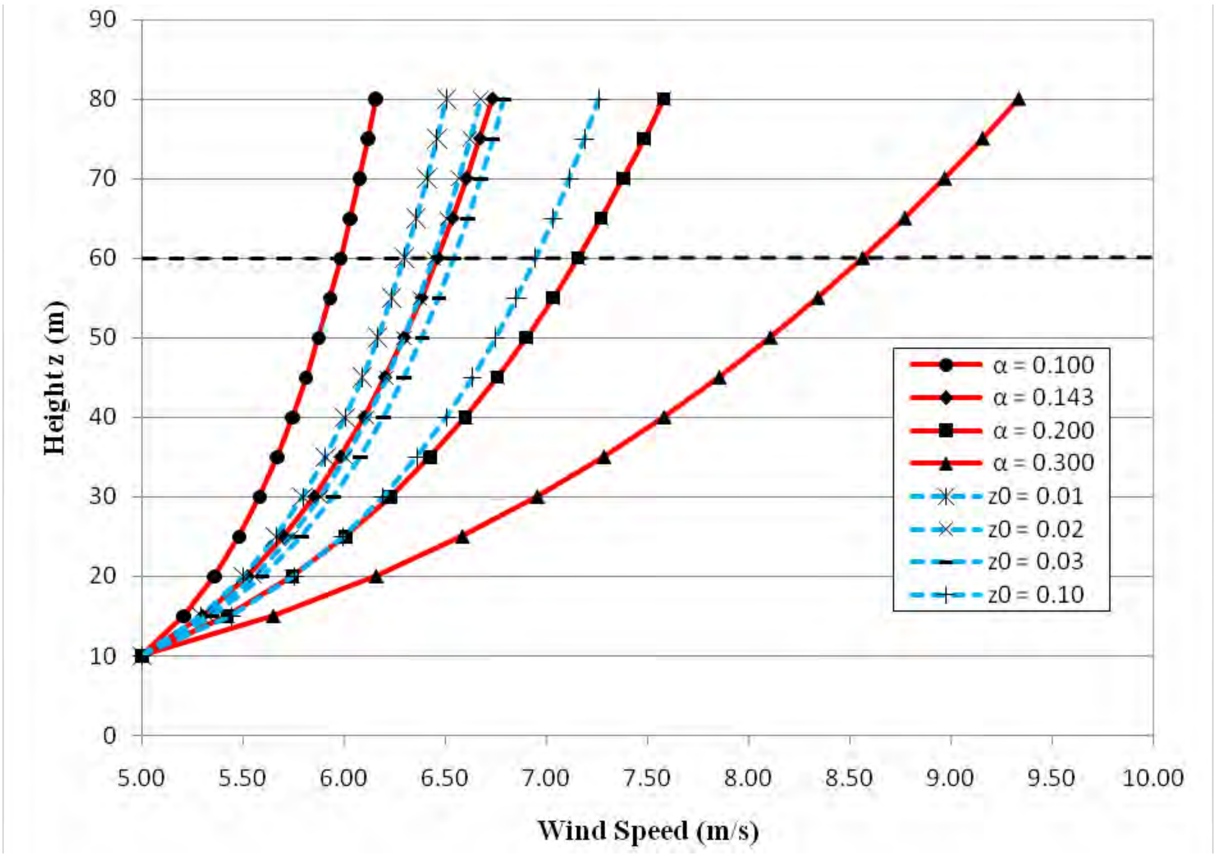


Figure 3- Graph illustrating the wind shear profiles under various log and power law parameters

5. Discussion

It is clear that the base case parameter choices (z_0 = 0.02m and α = 0.143) follow a near identical profile (Figure 3), and hence produce very similar capacity factor estimates and total amounts of energy annually (Table 2). This is to be expected, as both represent neutral stability conditions. The parameter values in this study were selected to represent the realistic values an analyst might take for the West Freugh site, as discussed earlier in the methodology. Through these choices a wider range of surface roughnesses than shear coefficients were applied (a percentage change of 1000% in z_0 and 300% in α respectively, from the lowest to highest values). Regardless of this disparity, which would be expected to favour a tighter knit set of results for the power law, Figure 3 shows that the range of extrapolated wind speeds at 60m was in fact considerably larger for the power law than the log law (0.65ms^{-1} and 2.58ms^{-1} respectively). This trend is also clearly observed in Figure 2(a) and (b); in the former, the wind speeds for each series are banded close together, in the latter they are considerably more widespread.

Figure 2 also very clearly illustrates the variable nature of the wind resource and the importance that it has on the output of a wind turbine. The sensitivity of the power output is pronounced for different shear coefficients, though relatively similar generation profiles are produced for the range of surface roughnesses, as shown in Figure 2(c) and (d). This is similarly observed in the clustered nature of the log law annual capacity factors in Figure 1, compared to a considerably wider range for the power law.

The reason for the pronounced difference in generation outputs, observed particularly strongly using the power law, is that wind turbine power is related to the cube of wind speed, so a difference in the wind speed error becomes far more significant in a generation calculation. This is best illustrated with an example; the mean 60m wind speed calculated for West Freugh in 2005, using α = 0.100 and α = 0.200, together with the limits of one standard deviation, is overlain onto a Vestas V80 power curve in Figure 4. As the cumulative energy generated is calculated by integrating under the area of the curve, it is clearly illustrated how a small change in mean wind speed estimate equates to a significantly larger area under the curve, and hence a large change in total generated energy.

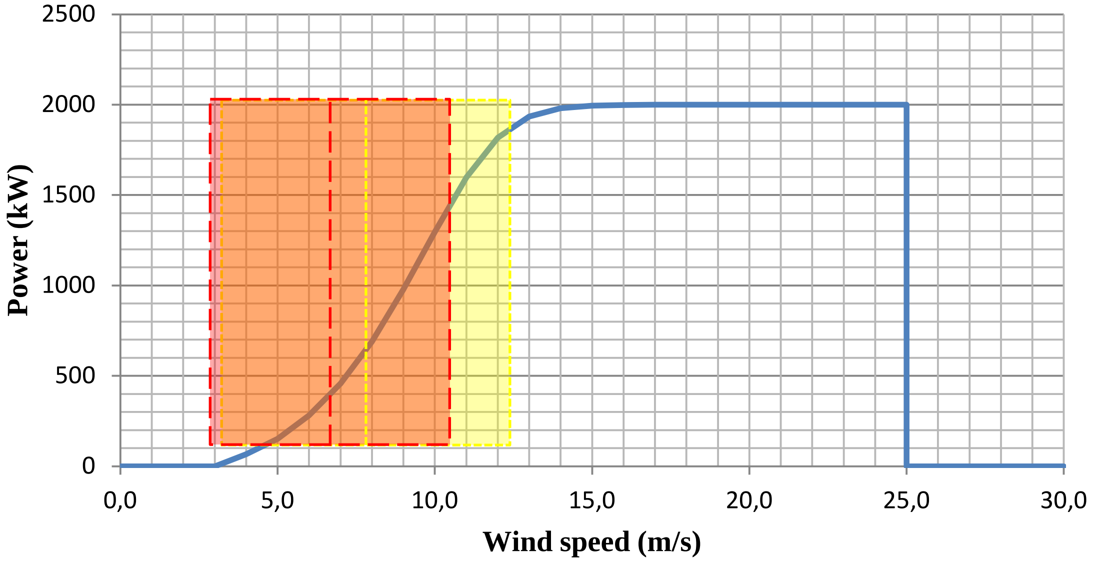


Figure 4- Vestas V80 power curve, annotated. The long red dashes indicate the mean wind and range of one standard deviation for α=0.100, and the short yellow dashes for α=0.200.

6. Conclusions

It is clear from the results that the wind shear coefficient is a more sensitive parameter than surface roughness, and that an equivalent percentage change to each value will impact the wind speed and generation estimates more robustly than when using the log law. However, if properly used, the power law can provide a more accurate idea of the renewable energy output of a particular site or area than the log law, which requires neutral stability conditions to be scientifically exact.

This study is not suggesting that either the power or log laws are intrinsically good or bad, but rather highlights the importance of the quality of information that goes into a model. It is important that there is a good understanding of the site before attempting to apply a single parameter to characterise the system, particularly as in reality the wind shear coefficient is a dynamic value dependant on a large number of parameters.

In order to understand the accuracy of using a single wind shear for the power law model, it is important to compare this theoretical generation data to the output for a real wind farm. Without this information, a critical analysis of this type of approach to future resource estimate cannot be made. Another interesting topic for future research will be to look into how different wind turbine designs, with different power curve characteristics, may change the energy yield of a site. Both of these are aspects of research that the authors intend to investigate in future studies.

Acknowledgements

The authors wish to thank James Cox of Pöyry Energy Consulting for clarifying aspects of the methodology used in their energy models. They also extend their thanks to Lauren Wheatley of AES, and to Thomas Campbell and Richard Mardon of Your Energy Ltd., for their business insight regarding the appraisal of wind sites.

References

[1] Pöyry, *Impact of intermittency: how wind variability could change the shape of the British and Irish electricity markets*. 2009.

[2] G. Sinden, "Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand," *Energy Policy*, vol. 35, no. 1, pp. 112-127, Jan. 2007.

[3] SKM, "Growth scenarios for UK renewables generation and implications for future developments and operation of electricity networks," BERR Publication URN 08/1021, Jun-2008.

[4] P. Meibom et al., *Final Report for All Island Grid Study Work-stream 2(b): Wind Variability Management Studies*. Roskilde, Denmark: Risø National Laboratory, 2007.

[5] ESB, *The Impact of Wind Power Generation in Ireland*. ESB National Grid, 2004.

[6] B. Klusmann and U. Ziller, *Power supply 2020 - how to reach a modern energy economy*. Bundersverband Erneuerbare Energie, 2009.

[7] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind Energy Explained: Theory, Design and Application*. John Wiley and Sons, 2010.

[8] M. R. Elkinton, A. L. Rogers, and J. G. McGowan, "An Investigation of Wind-shear Models and Experimental Data Trends for Different Terrains," *Wind Engineering*, vol. 30, no. 4, pp. 341-350, May. 2006.

[9] H. Panofsky and J. Dutton, *Atmospheric Turbulence: models and methods for engineering applications*. Pennsylvania State University: John Wiley and Sons, 1984.

[10] WAsP, "WAsP 9 documentation: The roughness of a terrain." [Online]. Available: http://www.wasp.dk. [Accessed: 22-Nov-2010].

[11] P. Gipe, *Wind power: renewable energy for home, farm, and business*. Chelsea Green Publishing, 2004.

[12] M.H. Albadi and E.F. El-Saadany, "The Effects of Wind Profile on Thermal Units Generation Costs," presented at the Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES, Seattle, WA, pp. 1-6, 2009.

[13] D. Sisterson, B. Hicks, R. Coulter, and M. Wesely, "Difficulties in using power laws for wind energy assessment," *Solar Energy*, vol. 31, no. 2, pp. 201-204, 1983.

[14] M. W. Tennis, S. Clemmer, and J. Etherington, *Assessing Wind Resources A Guide for Landowners, Project Developers and Power Suppliers*. Union of Concerned Scientists, 1999.

[15] L. Wheatley, T. Campbell, and R. Mardon, "Personal Communication with AES and Your Energy Ltd.," 2010.