ASSESSMENT OF THE WIND ENERGY POTENTIAL AT BAUSCH + LOMB WATERFORD

Author: John Flynn

Supervisors: Dr. Paul O'Leary & Dr. Éamon Molloy

BEING A THESIS SUBMITTED FOR THE DEGREE OF

Master of Engineering By Research (M.Eng)

Department of *Engineering*
Waterford Institute of Technology
Main Campus Cork Road, Waterford City, Ireland

Submitted to Waterford Institute of Technology, June 2013

Acknowledgements

The successful completion of this dissertation would not have been possible without the help of a great number of people. I would firstly like to thank my tutors Dr. Paul O'Leary and Dr. Éamon Molloy for their support and knowledge provided throughout the course of this project. They have both been instrumental in shaping the outcome of this work. Secondly, I would like to thank Bausch + Lomb as a company for their support throughout this work both from a resource and a financial perspective, particularly the D&R department and the facilities department.

Finally I wish to thank my family and friends for providing the support and motivation I needed to complete this project successfully.

Table of Contents

Figures & Tables

Figures

Tables

Statement of Confidentiality

This document was submitted in fulfilment of the requirements for a masters of Engineering (M.Eng.) by research at the Waterford Institute of Technology (W.I.T).

Declaration of originality of dissertation and acknowledgement of assistance

I, John Flynn, affirm that this dissertation is my own work, except where otherwise acknowledged in the text. I also confirm that I have fully acknowledged by name all of those individuals and organisations that have contributed to the research for this dissertation.

Signed:... Date:…………………………

Abstract

In recent years, renewable energy has come to prominence due to worldwide concern over greenhouse gases, energy supply issues and increasing economic volatility, and this, coupled with the ever-increasing price of fossil fuels, has led to an increased emphasis being placed on alternative sources of energy. These energy issues are attributable to a number of factors, typically, dependence on fossil fuel reserves, increase in energy demand and the current economic climate. As a result of the factors mentioned above, a greater reliance has been placed on alternative energy sources.

Wind is an abundant potential source of energy in Ireland. Wind is, however, extremely variable in nature, as is also, albeit to a lesser extent, the national demand for electrical energy. Harnessing and predicting the electrical power from wind is the challenge, especially as Ireland's electrical power from wind is going to significantly (more than 70-fold by 2050, according to one roadmap) increase over the next few years.

Allied to the abundant nature of wind resources in Ireland and the increasing levels of national grid penetration that wind energy is currently experiencing, electricity auto production, where the wind generated electricity is for local, private use, is becoming ever more prevalent. Furthermore, electricity auto production will form a key component in the distributed generation of future smart electrical grids and is even now an attractive option for users with large energy demands, primarily to reduce their energy costs with a small generation surplus to on-site demand being exported to the grid.

1: Wind energy

The scope of this project includes the specification, purchase and erection of a suitable wind measurement mast aligned to budgetary and timing constraints, the monitoring of wind speed and direction at specified heights, while undertaking statistical analysis of the data using multiple software packages over a 36-month time period. The data generated from the Bausch + Lomb site has also been compared to regional and national data and short term forecasting methods, and the effects of wind shadowing have also been investigated.

The wind measurement mast has the capability to measure both wind speed and direction at heights of 6m and 10m. To date 36 months worth of data has been collected which amounts to in excess of 200,000 data points. The measurement system is shown at the Bausch + Lomb manufacturing facility in Figure 1 and Figure 2.

Figure 1 Overall Mast layout at the B&L site

Figure 2 Wind sensors located at 6m and 10m

The renewable energy sector has become very prominent in Ireland in recent years, due mainly to the abundant supply of natural resources, mainly wind, and also the need for a cleaner, cheaper energy supply. Although wind is an abundant source of energy in this country, it is also variable in nature. Harnessing and predicting the electrical power from wind is a challenge, especially as the electrical power from wind and the penetration of wind power in to the overall grid infrastructure is going to significantly increase over the next few years.

1.1 The importance of renewable energy

In recent years there has been increased awareness surrounding the variety of energy issues faced by Europe and the rest of the world, such as:

1. Dependence on foreign supply of natural resources;
2. Economic issues – price of a barrel of oil now currently sits at $104.63 (RTE 2012).
3. Energy sustainability issues; at some point fossil fuels will run out.

As a result of the factors mentioned above, a greater reliance has been placed, of late in particular, on alternative energy sources. Wind energy has experienced an increased level of awareness, in that wind energy has exhibited the most rapid growth of all renewable energy sources in the last number of years. This rapid growth has been particularly prevalent in one of the largest economies in the world, the US. Wind energy is also gaining more prominence in Western Europe, where Denmark leads the way in terms of wind energy contributions to total energy production in a particular country.

1.2 Project background

This work began as a collaboration between Bausch + Lomb and Waterford Institute of Technology (W.I.T). In preparation for this body of work a wind measurement mast was purchased by Bausch + Lomb and installed on site and the preliminary data gathered from the mast fed in to an (ultimately) successful research proposal for this work.

1.3 Objectives

The objectives of this project are as follows: -

- Specify and purchase a suitable wind measurement mast according to specified budget and timeline.
- Real time monitoring of wind speed and direction at 6m and 10m respectively.
- Undertaking statistical analysis of data incorporating analysis of parameters long term to confirm accuracy.

- Estimate the energy potential of the site.
- Investigate forecasting.
- Investigate the shadowing and averaging errors in wind auto production analysis.

1.4 Wind- Importance of wind in Irish life.

Presently, there are 179 wind farms on-line and operational, in the Republic of Ireland (IWEA 2012). The first wind farm project was established in 1992 at Bellacorrick in Co. Mayo. At present, there is a peak capacity of 2054.86 Megawatts (MW) connected to the Irish electrical grid. Due to the 'quantity' of wind in Ireland, this installed capacity should produce about 30% of the peak value. The figure of 30% is known as the capacity factor and is usually much lower in other countries, for example Germany's was 19% in 2009. However, the trend with wind turbines has been to go ever higher into the sky with larger swept areas, which lead to higher capacity factors across the board.

The European Union (EU) has established a strategy to reduce the effects of climate change and establish a common energy policy. By 2020, it is required that renewable energy should account for 20% of the EU's final energy consumption. In order to meet and or exceed this common target, each member state will need to increase its production and use of renewable energy in electricity, heating and cooling and transport (European Renewable Energy Council 2011).

In order to achieve 2020 targets for renewable energy an estimated 5,500 – 6,000MW of wind generation is required (SEAI 2012). The two main organisations which are concerned with renewable energy in Ireland are the Irish Wind Energy Association (IWEA) and the Sustainable Energy Authority of Ireland (SEAI). Currently the government has given a commitment that 40% of our electrical energy needs will be from renewable sources by 2020.

2: Literature Review

2.1 Wind energy Overview

A dramatic increase in wind generated electricity in Ireland is proposed by the Sustainable Energy Authority of Ireland (SEAI) in their *Wind Energy Roadmap up to the year 2050* publication and is displayed Figure 3 (SEAI 2013). This increase is proposed to substantially exceed Ireland's electrical energy demand, with the surplus energy exported to Great Britain and, subject to a new interconnector being installed, to France.

Central to realising the full potential of the projected growth in the wind renewable energy sector is the availability, quality and quantity of wind itself. Ireland has one of the strongest wind energy potentials in Europe, and one of the best resources in the world (McHugh, 2010). It is abundantly clear that Ireland's total installed wind capacity will require significant ramp up (as depicted by the red circles to the left and right of figure 3) in order to meet the 2050 commitments of having a capacity of greater than 10GW of onshore wind production as shown in Figure 3. Wind energy will therefore be a key contributor and a vital element of Ireland's energy infrastructure in the future (SEAI 2013)

Having detailed the importance and prominence of wind energy in this country, the next section will outline the origins of wind energy.

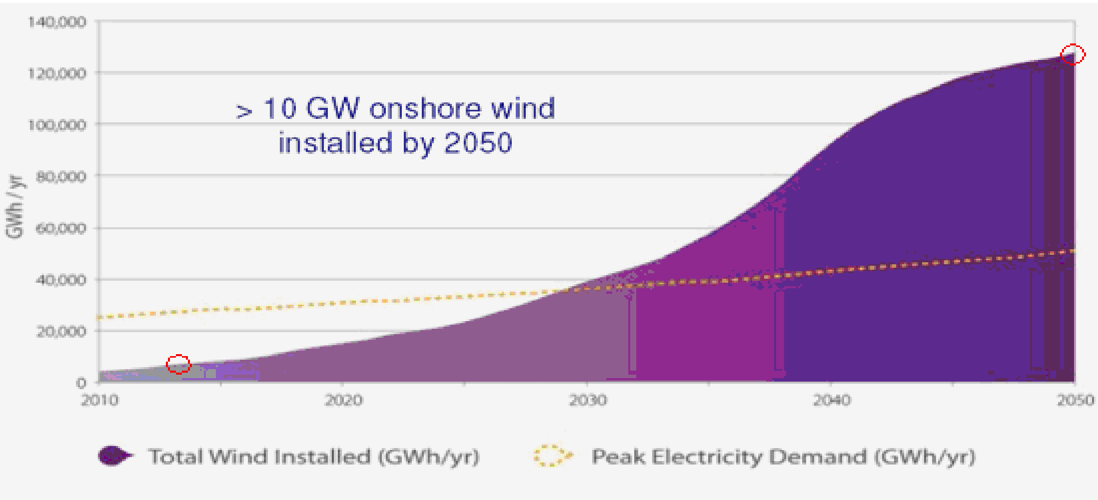


Figure 3 SEAI wind energy roadmap to 2050 (SEAI 2013)

2.1.1 The origins of wind energy

The movement of air or wind energy occurs due to pressure differences that exist in the atmosphere or due to pressure gradient forces (PGF), governed by the second law of thermodynamics, which states that higher energy systems will always be attracted and transferred to lower energy systems. This movement between high and low energy systems produces wind energy. The transfer or movement of air between a hot and a cold location causes wind energy.

There are a number of factors, which contribute to the strength of wind energy; these are centrifugal/centripetal force, differences in land mass composition where changes in topography can accelerate or decelerate wind speeds; also surface roughness variations occur as a result of this land mass variation (Bianchi *et al* 2007). Variations in surface roughness and the associated knock-on effects can have a large impact on wind speeds, which will be outlined in detail in the next section.

2.1.2 The surface roughness variation/the physics of wind

One of the major consequences in surface roughness variations or the surface roughness factor is that wind shear can result, which has the effect of decreasing the wind speed nearer the earth's surface (this effect is more prevalent in cities or built up areas). The higher up in the atmosphere, the lesser are the effects of wind shear, conversely, closer to ground level the effects of wind shear are more pronounced (Dowley 2010).

Moreover, closer to ground level, the surface roughness factor can alter the rate at which the wind speeds decrease. Rougher surfaces tend to decrease the wind speed faster than smooth surfaces as depicted in Figure 4.

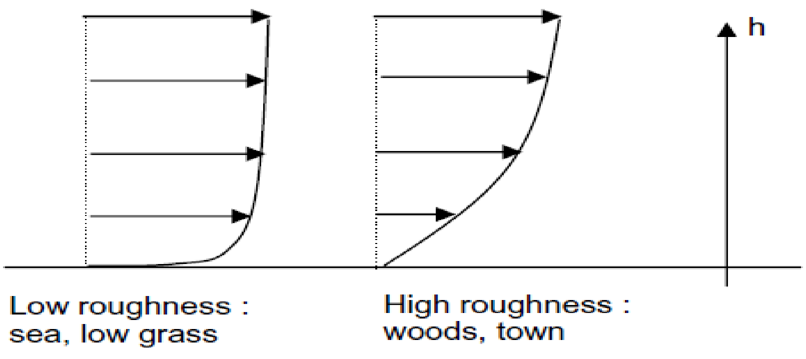


Figure 4 Higher surface roughnesses cause more rapid wind speed decreases. (Dowley 2010)

Thus modern wind turbine developments typically are continually increasing hub heights, currently at over 100m, but up to 250m by 2050, according to the SEAI roadmap's projections, to take advantage of the greater and more even wind speeds that exist higher up in the atmosphere (SEAI 2013)

The movement of air between high pressures and low pressures is represented by isobars on a weather chart. The proximity of these isobars to each other on the chart directly relates to the strength of the wind. The closer the isobars are to each other, the stronger the wind is (greater difference in pressure gradient), while the more spread out the isobars are, means that there is a decrease in the strength of the wind.

The wind generated by these pressure gradients are what drives wind turbines and the by-product of this is useful energy which will be discussed in the next section.

2.1.3 Wind turbines

Wind turbines or Wind Energy Converters (WECs) convert the wind energy passing through the turbine blades into useful electrical energy output. Wind turbines are broadly classified into two main types, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). HAWT type turbines enjoy a greater level of commercial prominence than their VAWT counterparts (Barnard 2013).

One major consequence of wind energy or the supply of wind that the turbine witnesses is that the supply is highly variable in nature; wind does not occur as a constant supply and instead is variable. Moreover, turbines have a cut-in speed and a cut-out speed. The cut-out speed is there to protect the turbine from destruction and is typically about 25m/s. The minimum cut-in speed can be about 3-4m/s and is due to a combination of reasons, including inertia, but as such these speeds contain little energy, are not a significant loss at any given time, unlike the cut-out speed, which represents a significant loss in energy at any given time (Wind Power Program 2011).

The main limiting factor associated with wind turbines is their theoretical maximum operating efficiency as defined by the Betz limit, which states that the theoretical maximum power that can be extracted from the wind is 59% of the actual power, although in practice the extracted power is less than this limit. The Betz limit is expressed in the following format.

$$C_{p_{\max}} = \frac{\max.\ power\ extracted}{power\ available} = \frac{\frac{8}{27}\rho A v^3}{\frac{1}{2}\rho A v^3} = \frac{16}{27} = 0.5926$$

(Betz 1966)

One of the most important components of the wind turbine assembly and one which the Betz limit directly affects are the turbine blades. The physics of the turbine blades will be discussed in the next section.

2.1.4 Wind turbine blades

The wind turbine blades capture the on-rushing wind, and operate along the same aerodynamic principles as that of the wing of an aircraft. The shape of the turbine blade and the shape of the aircraft wing are very similar in appearance.

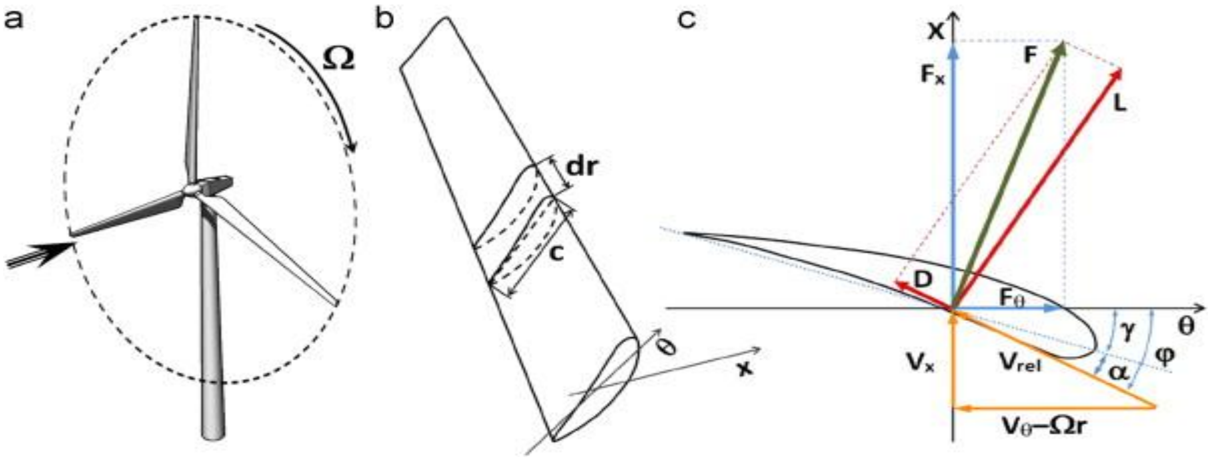


Figure 5 Lift and drag characteristics for wind turbine blade (Porte-Agel,F *et al* 2011)

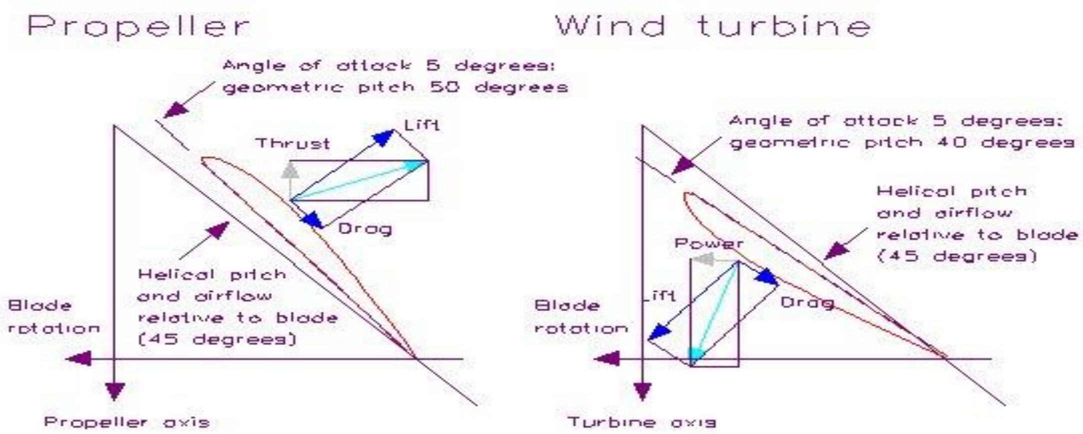


Figure 6 Lift and drag characteristics for wind turbine blade section (Gregorie 2002)

The cross-section of the wind turbine blade is essentially an airfoil, where the effects of lift and drag are constantly at play as outlined in Figure 5 and Figure 6. Figure 5 outlines for the direction of the oncoming relative wind with respect to the airfoil, that the lift and drag components work perpendicular to each other (Porte-Agel,F et al 2011). Figure 6 compares an aerofoil section for a propeller and a wind turbine, where it can be seen again that the lift and drag components work perpendicular to each other also (Gregorie 2002).

The shape of the wind turbine blade has evolved and is designed in such a way as to maximise the potential of the wind turbine blade to generate electricity. As already mentioned, wind turbines are, at present, ever increasing in hub height. Consequently, the other major component of the wind turbine assembly, namely the blades, have also increased in length, thereby increasing the turbine swept area and thus increasing the potential to generate larger amounts of electricity.

2.2 Autoproduction

Wind energy is most abundant in the west of Ireland, only slightly less so in the South East region, where the Bausch + Lomb manufacturing plant is sited, in the IDA industrial facility in Waterford. The size and scale of the Bausch + Lomb plant, along with the presence of some unused terrain on the site, led to the exploring of the feasibility of an autoproduction wind turbine installation.

With autoproduction, the fluctuations in the energy source do not have an immediate impact on the plant's electrical supply, as imbalances between supply and demand are usually made up by the external electrical energy supplier (Boyle *et al* 2007) and thus transmission losses are reduced (Van der Vleuten *et al* 2006). Simply put, for Bausch + Lomb, there is a large 24/7 load, so any typical single wind turbine would never exceed the B&L load and always only partially contribute to the total demand. Figure 7shows an example of an autoproduction installation at a B&Q outlet in the UK, as part of Ecotricity's energy installed autoproduction portfolio (Ecotricity 2012)

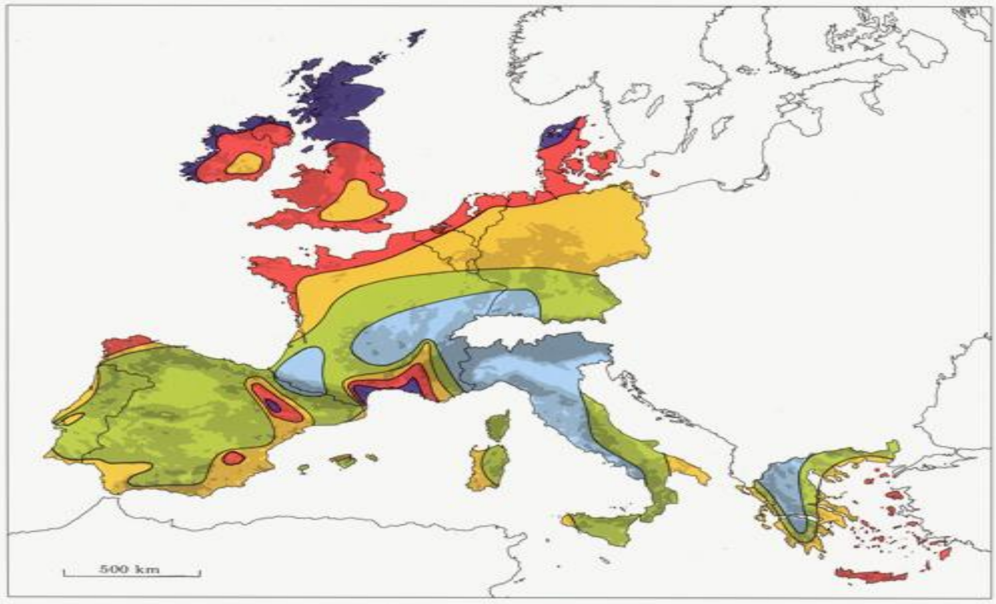
A case study in the Irish energy network could be that of Munster Joinery described in the Wind Energy Direct report (Wind Energy Direct 2013). This report outlines the importance and the advantages associated with wind autoproduction when harnessed by industrial sites.

Figure 7 Autoproduction installation at a B&Q facility in the UK (Ecotricity 2012)

2.3 The prominence of wind turbines in Ireland

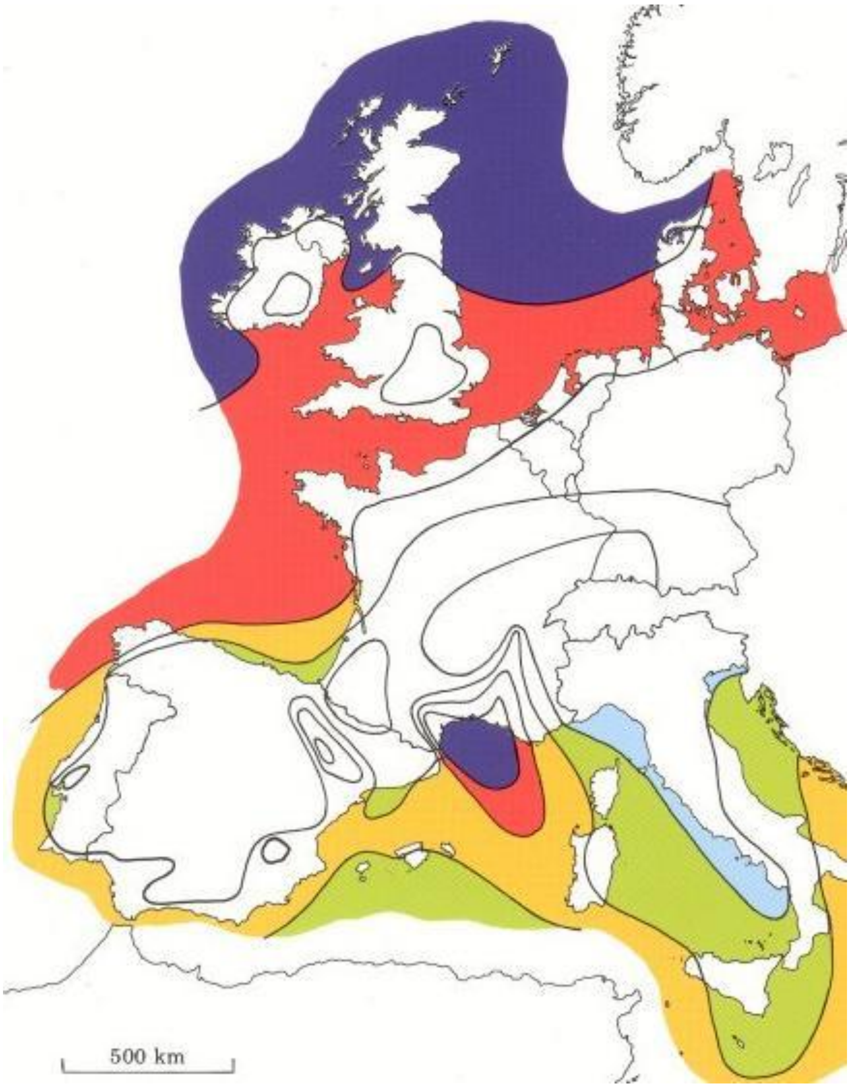
16 –20 % of Ireland's energy consumption is to come from renewable sources by the year 2020 according to the EU 2009 Renewable Energy Directive (DCENR 2011). There will be three main components to this 2020 target, renewable energy in electricity (RES-E), renewable energy in transport (RES-T) and renewable energy in heat and cooling (RES-H). In Ireland the targets are for renewables to contribute to 40% of the RES-E targets, 10% to the RES-T targets and 12% to the RES-H targets (White 2011)

Ireland and the United Kingdom (UK) have an abundance of natural wind renewable resources with capacity factors of up to 30% in comparison with mainland Europe at figures as low as 17.5% (Boccard 2008). These capacity factors are likely to increase with the installation of taller, larger turbines and also turbines out at sea, where the lower surface roughness leads to lower wind shear. Figure 8 shows the abundance of wind resources on land over all typical terrains, in both Ireland and the UK, relative to most of the rest of Europe. Figure 9 shows the offshore wind resources with reference to the same countries that Figure 8 relates too. A key element of this graph is how both Ireland and the UK lead the way in terms of offshore wind resources to a similar extent as the onshore wind resources.



	Wind resources[1] at 50 metres above ground level for five different topographic conditions									
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 8 European Wind Atlas (Onshore), (Wind energy the facts 2012)



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure 9 European Wind Atlas (Offshore) (Windea 2012)

A consequence of the abundance of wind resources available in this country is that a number of start up companies have been formed such as ITL in Tralee and Arklow Marine, which specialise in the Operations and Maintenance (O&M) of the Arklow bank offshore wind turbines and in the UK also (Windea 2012). Additionally Enterprise Ireland see wind generated electrical energy as a viable export market, which will grow considerably in the near future, primarily to Great Britain, but possibly also through direct export to France (SEAI 2013).

Waterford has one of the lowest renewable wind energy grid contributions in the country at 1.72MW. The strongest counties in terms of wind energy development are Cork, Kerry and Donegal (IWEA 2013) In Donegal, County Council income from rates from wind energy sites make up as much as 30% of the annual intake at approximately 30 million Euros per annum.

Ireland and more specifically the East coast of the country has a distinct advantage in terms of the development of offshore wind turbines, by the fact that shallow waters exist there of approximately 20m or less in comparison to other ocean regions where water depths can be as deep as 200m (Edwards *et al* 2010). The costs of the development and installation of offshore wind turbines can rise greatly as the depth of water to which the installation is to take place increases (Harvey *et al* 2001)

One of the main obstacles to Ireland achieving its 2020 targets is grid availability, allied to the planning process. Often, where there are very good wind resources grid availability and support is very limited. It is anticipated that getting grid connection to these areas could take up to 7 – 10 years (Deloitte 2009).

There are a number of important developments taking place in the coming years in the South East region, which will make a large contribution to achieving the 2020 targets. These developments include the current round of approved applications for electrical grid connection, known as the Gate 3 scheme (IWEA 2013). Additionally, Eirgrid as part of their Grid 25 program have identified a number of grid developments to include: strengthening of the network links to Dublin and Cork and the strengthening and re-enforcement of current grid infrastructure linking the towns and cites in the region (Eirgrid 2013). Recently, a major milestone for wind-generated electricity has occurred with the completion of the 500MW East – West Interconnector, which forms a power link between Ireland and the UK (Foley *et al* 2009). This is the second interconnector linking the two islands, following the 500MW Moyle interconnector, from Northern Ireland to Scotland (Harvey *et al* 2001). These interconnectors will permit Ireland to export excess wind power, as well as open up competition in the Irish market, by permitting sale of British electricity here.

2.4 Wind turbine prediction and methods

Wind is a plentiful and non-exhaustible source of clean renewable energy. However, there are disadvantages associated with this type of renewable energy, the main issues being that the wind speeds produced are non-uniform (there are plenty of peaks and troughs associated with it) (Boyle *et al* 2007) high wind speeds are not always guaranteed, prolonged periods of lulls can be common also. The demand for electrical energy is also non-uniform, varying throughout the day, the week and, of course, throughout the year. In a nutshell, the energy available from renewable wind energy is not uniform, nor is the demand for this energy (Boyle 2007).

The key issue/factor is being able to balance/match supply with demand, so when demand is at its peak then so too ideally would be supply, thus reducing the amount of energy needed to meet demand sourced from conventional generators. Intense efforts have been poured in to wind prediction methodology (Sanchez *et al* 2006). There are some wind prediction methods currently being employed, which try to predict the wind energy availability in advance, so that electrical grid planners can plan ahead to match supply with demand (Eirgrid 2013).

The graphs shown in Figure 10, Figure 11 and Figure 12 illustrate the global energy demand, wind generated supply versus demand, daily wind production and wind penetration across 7 EU countries (Cherfurka 2013).

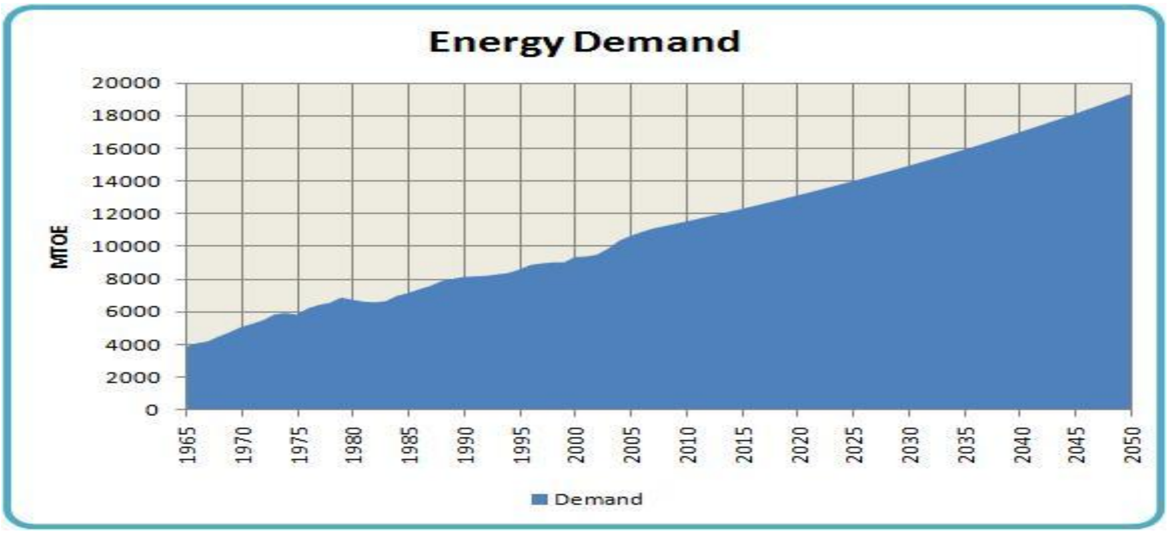


Figure 10 Energy supply versus demand (Cherfurka 2008)

Figure 10 outlines the increase globally in energy demands in terms of millions of tons of oil equivalent (MTOE) from 1965 to 2008 and then forecasted levels through to the year 2050. If one assumes the forecasts are correct, then energy demand will continue to steadily increase. The demand for wind energy sources will most likely also increase (spurred on also by national and international targets), which will in turn add greater importance to issues of stability of supply.

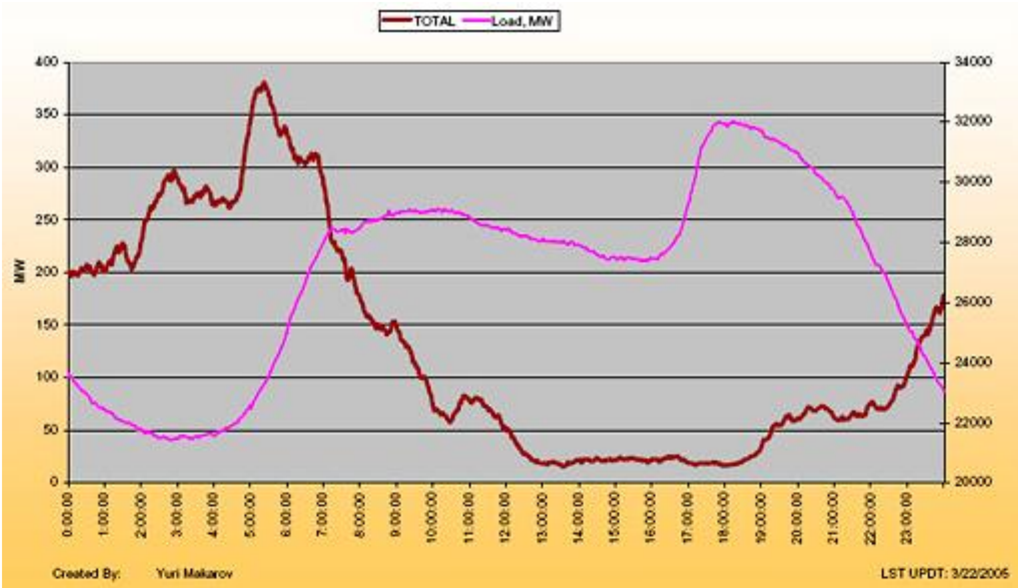


Figure 11 Wind energy production versus consumption in California, January 2005 (Windbyte 2012)

As alluded to previously, the issue of stability of supply is an important one, in order for a secure and dependable supply network, variability in supply has to be kept to a minimum. The graph illustrated in Figure 11, compiled by the California Independent system operator in 2005, outlines for a 24-hour period the total wind energy production (indicted by brown line), versus the energy consumption for that same period (indicated by pink line). For this particular day, peak production occurred during a period of low consumption between the hours of midnight and six in the morning. Between the hours of greatest consumption, five in the evening and nine at night, production was at its lowest and gradually began to rise again towards midnight. This is an example of the variability that can be encountered in wind energy production and how it may be completely out of phase with the demand.

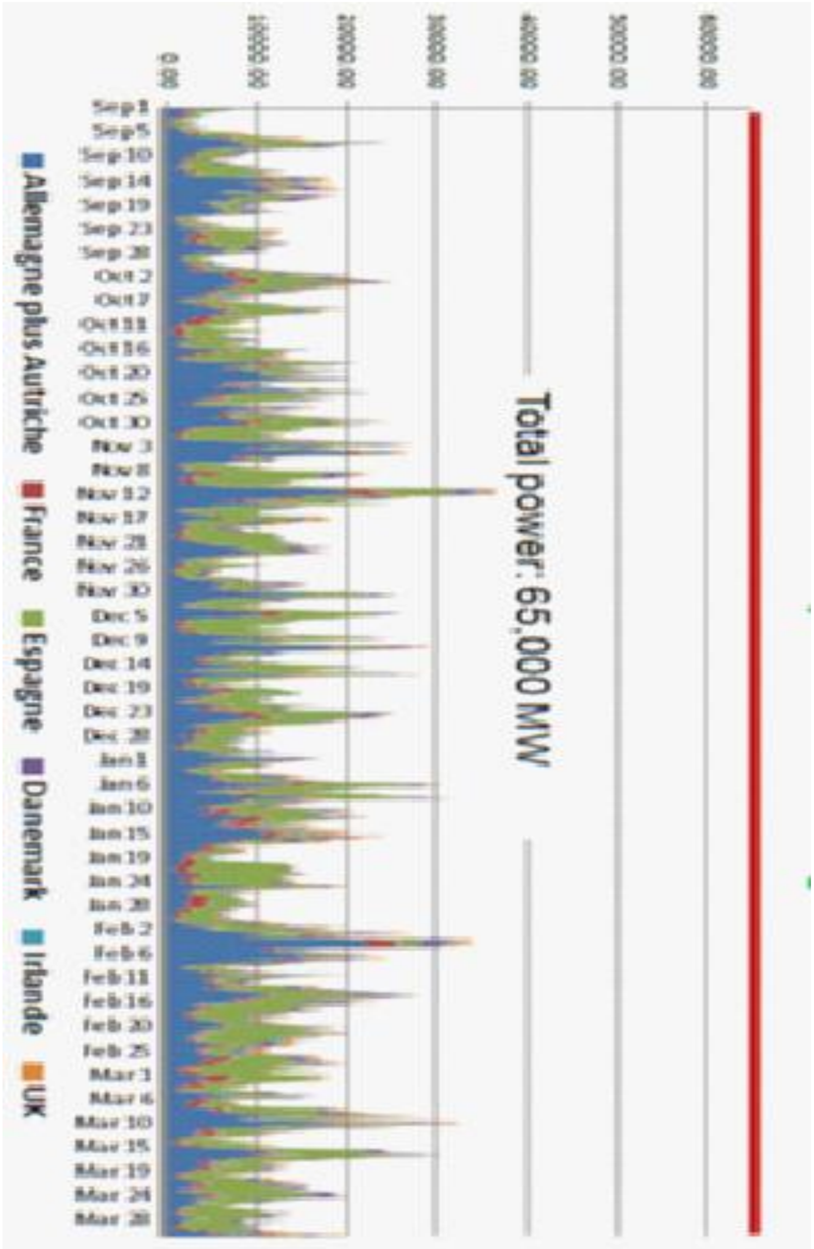


Figure 12 Winter 2010/2011: Variations of wind production across 7 EU countries (Windbyte 2012)

The total wind production for a six-month period September 2010 to March 2011 is illustrated in Figure 12 along with the variability in output. This very recent body of data taken from prominent European countries outlines the variability in wind production across a range of European countries, helping to underline that geographic diversity may not always be sufficient to mitigate against fluctuations in wind generated electricity onto the European grid. The issues of variability/stable supply means that wind energy still has an amount of improvement required to catch up with more dominant, traditional forms of energy from its relatively low contribution as outlined in Figure 13. Figure 13 shows the contribution of renewable energy and more specifically wind energy to the overall energy consumption for the US for 2011 (EIA 2012).

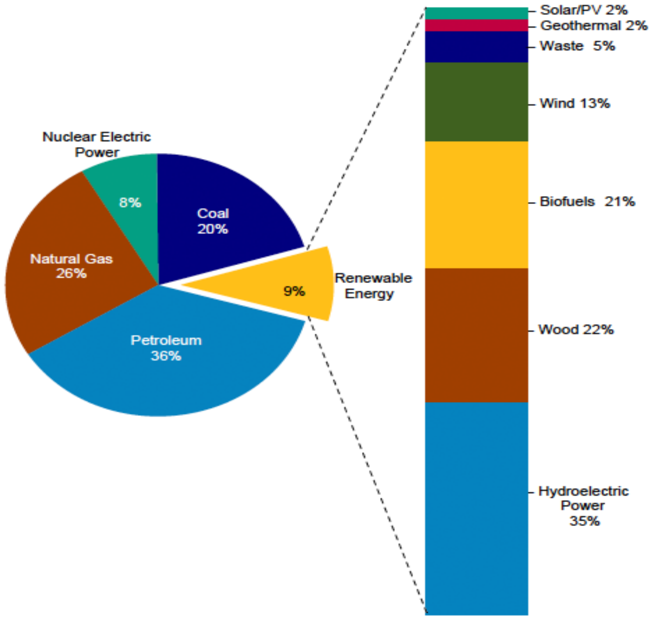


Figure 13 Annual energy breakdown for the United States for 2011 (EIA 2012)

However wind energy is gaining increasing penetration year on year globally, particularly in European countries like Denmark, Portugal, Spain and Ireland, which is clearly illustrated in Figure 14 (Wind power engineering 2013).

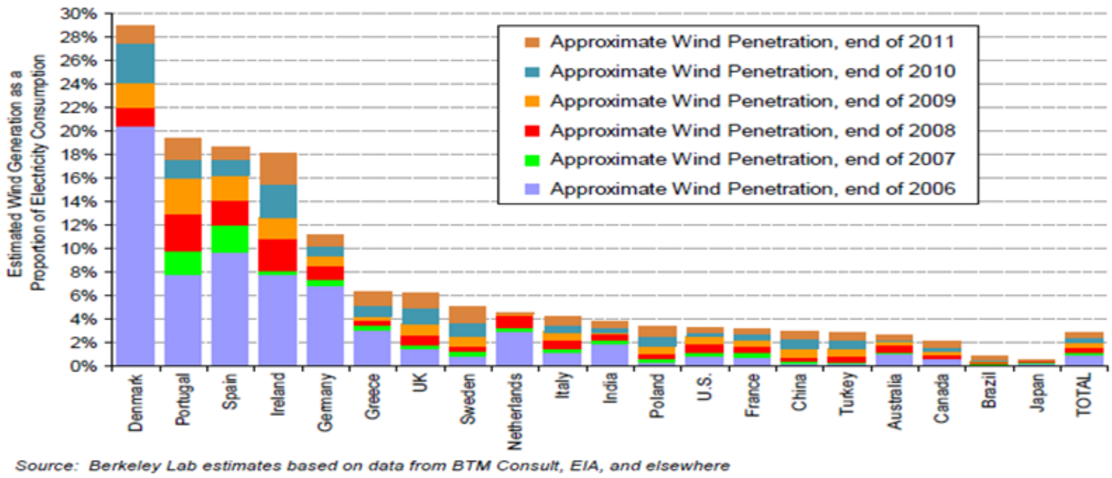


Figure 14 Wind energy penetration for twenty countries with the most prominent installed wind energy capacity (Wind power engineering 2013)

Wind energy prediction is of significant importance in the renewable energy industry, the ability to be able to forecast future demand and match this to supply levels is very important. Wind power forecasting is an important tool in addressing the challenges of supply and demand.

As wind is a variable power supply it is therefore difficult to integrate this resource on a large scale into electrical grids (Brazilian *et al* 2004). As the proportion of electrical energy supplied by wind power increases so too will the impact of its variability. The electrical grid is constructed with stable power sources in mind; therefore wind needs to be more stable as a result, or at least the consequences of its variability mitigated. In the case of relatively small power systems such as Ireland's, with a limited wider grid interconnection, the problems of variability in supply have a greater effect on the system (Lang 2008) 'The inability to spill excess generation to neighbouring power systems will make balancing power on the island (north and south) difficult with such high wind penetration. With current growth rates in wind installations, there may be a need to curtail power output at times, if no other measures are taken to assist in the penetration of wind'. (Lang 2008).

As wind power generation will increasingly contribute, forecasting wind will take on a greater importance as a result. This can be attributable to a number of factors, mainly to security and stability, and, of course, reducing economic penalties for wrongly declared power outputs.

There is a number of forecasting/prediction methods currently being employed successfully, which range from more complex modern software tools such as Neural Networks (NNs) and Support Vector Machines (SVMs) models to the more traditional forms of wind analysis such as the persistence prediction method (Chang *et al* 2011)

This thesis will aim to carry out a short-term prediction procedure based on historical collected data. In general, forecasting techniques can be broadly divided into short term, medium term and long term forecasting. Depending on the timescale, the approach used will differ. Short term forecasts tend to be of the order of a couple of minutes to 1 hour, medium term forecasts tend to be of the order of 24 hours, while longer term forecasts can be of the order of 24-72 hours. Another differentiating factor with regards to forecasting, is the method employed. Forecasting methods can either be physical or statistical. One of the most common approaches to physical prediction would be the NWP method (Numerical Weather Prediction). This method evaluates physical input variables and utilises specific statistical packages to produce output predictions. NWP models are forecasts based on objective calculations derived from a set of physics based equations (Britannica 2012). This process was developed by a British Scientist named Lewis F. Richardson; shortly after World War

One. However, this ultimately proved unsuccessful, although it did pave the way for further development of the methods. As computing power and capability grew, so did the complex nature of the calculations as part of NWP modelling.

Statistical approaches to prediction evaluate historical data, apply it to a pre-constructed statistical model and produce output predictions. The main statistical approaches which are broadly employed in the wind energy prediction sector are the ARMA (Auto Regressive Moving Average) and the ANN (Artificial Neural Network) methods.

The idea of very short-term forecasting methods was investigated as part of this thesis. The persistence method is the most common and the easiest to apply of the short-term statistical forecasting methods. Persistence is based on the principle of whatever occurred previously is most likely to occur in the immediate future. The persistence method can be successfully applied to data sets with relatively short time intervals, as is reported in this study with time intervals of 10 minutes. Therefore applying the Persistence approach dictates that the wind speeds which occurred 10 minutes ago are more than likely to occur 10 minutes into the future.

2.5 Summary

Over the coming years, renewable energy, in particular wind energy will contribute ever more to energy demand in the Republic of Ireland according to the SEAI (SEAI 2013). Central to the increased levels of wind energy penetration, will be Ireland's commitment to its EU 2020 targets (DCENR 2011) and the development of international grid interconnections allied to an abundance of natural wind energy resources (Foley *et al* 2009)

In the interim there are a number of varied challenges, which need to be overcome in order for wind to become such a key component in Ireland's efforts to meet its energy targets. These include funding, planning, legislation along with the inherent challenge of matching supply and demand.

In terms of wind feasibility and prediction, the Weibull distribution is the most suitable fit to characterise the wind speeds, in that it is essentially a probability distribution (Chang *et al* 2011). For desk-based analysis and real-time wind monitoring the effects of shadowing and the consequent spike for no and low wind speeds should not be ignored. This will also be considered in the next chapter.

3. Test set-up and associated theory and methodology

Evaluating a potential site for future wind turbine installation requires reliable wind measurement and analysis of this wind data in terms of power calculations, including the variation of air density with temperature and pressure, the power coefficient C_p, the maximum power co-efficient, the Betz limit, and the Weibull distribution. The Weibull distribution is a very effective means to characterise the variability of wind speed distributions.

The experimental set up and data collection system is outlined in section 3.1, and consists of a wind mast and accompanying data logger set up. The wind mast, data logger specifications, wind speed distributions, the power in wind and analysis methods are dealt with in sections 3.2 to 3.5, respectively.

3.1 Data Collection system

The data collection system (shown in Figure 15) begins with the calibrated wind monitoring sensors located on the 10m wind mast at heights of 6m and 10m recording the wind speed values and directions in the form of a pulse. These are relatively modest heights compared to conventional monitoring in the wind industry, which are typically 50m high. A time-stamped wind-speed is registered in the data logger, which is also mounted on the wind mast, and the values are then temporarily stored on the data logger's flashcard. The flashcard is periodically manually removed to analyse the recorded data. This data can be later processed in bulk using the data logger software, the *R* programming language, Minitab and MS Excel.

The logging software is configurable to sample at intervals ranging from 10 minutes to 1 hour, registering the maximum, minimum and average wind speeds in the chosen intervals and also standard deviations. This system can therefore produce as much as 36,000 data points per annum. In the work presented here, the chosen interval was 10 minutes.

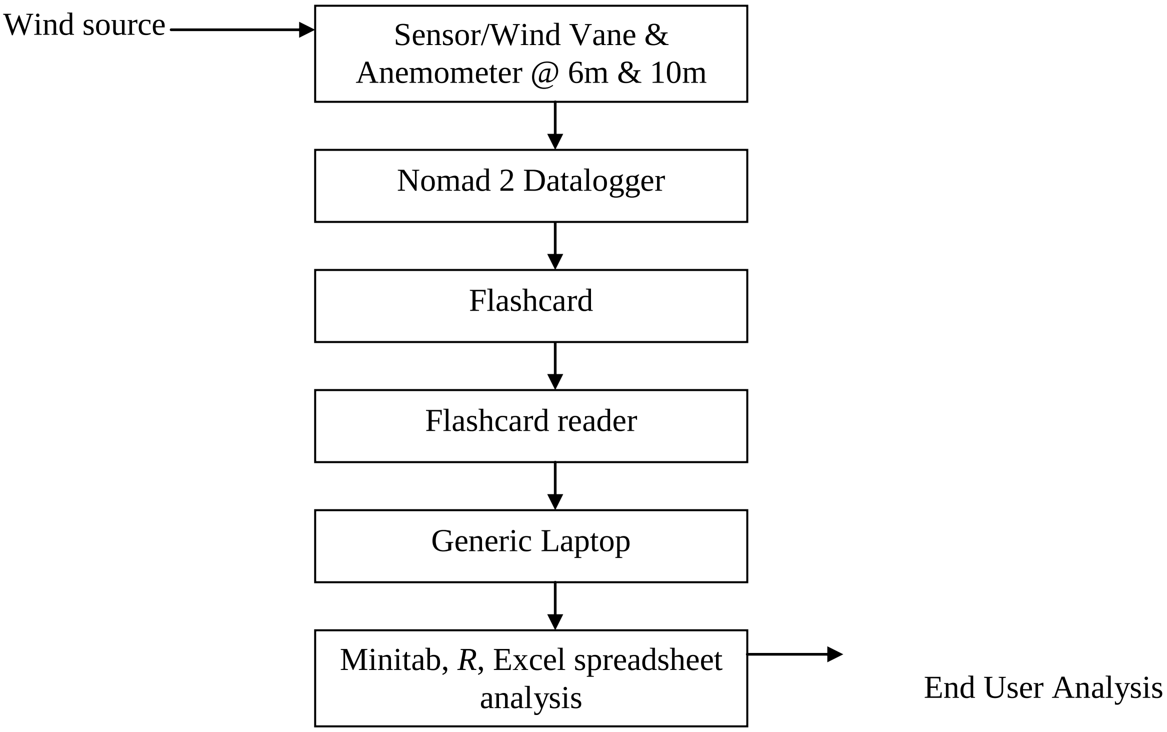


Figure 15 Block diagram of the data acquisition system

3.2 Wind mast and data logger specifications

The wind data collection system consists primarily of a 10m Nexgen wind mast coupled to a Nomad 2 data logger, along with the other ancillary elements of the installation such as the guy wires, the central ground base mounting plate and the ground anchor points for the guy wires. All of these elements are pictured in Figure 16, Figure 17 and Figure 18 which depict the wind mast installation at the Bausch + Lomb contact lens manufacturing facility at the IDA industrial estate in Waterford City.

Figure 16 Nomad 2 data logger

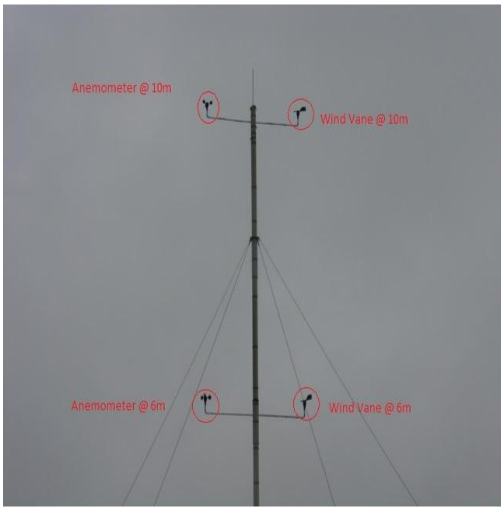


Figure 17 Wind vane & anemometer

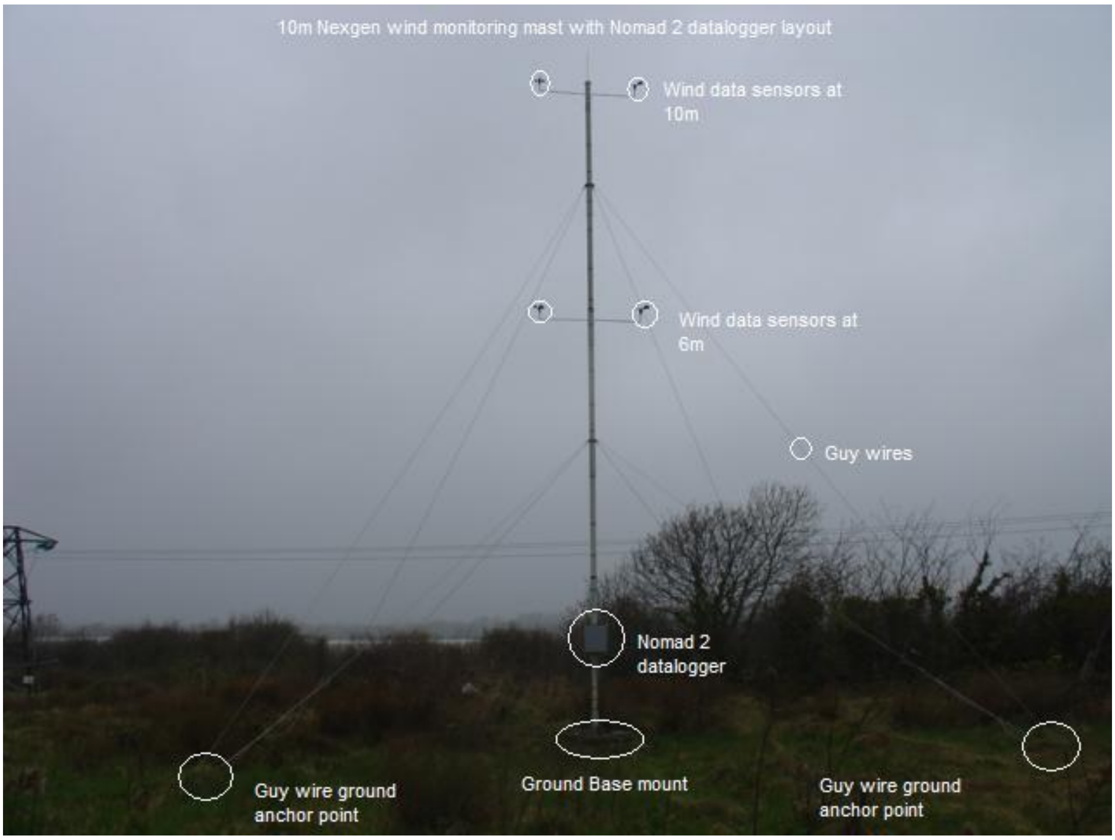


Figure 18 Wind mast installation at the Bausch + Lomb manufacturing facility

Figure 16 and 17 show the Nomad 2 data logger, wind vane and anemometer arrangement at 6m & 10m, respectively. The 10m Nexgen wind mast is of a heavy-duty plastic construction that ensures both strength and ease of portability. This is a class one mast installation, which can in theory withstand windspeeds of up to 240 km/h, so in theory it should survive harsh environments. The mast is anchored in to position using four anchor points, with steel guide wires connecting the mast to the anchor points. These anchor points and guide wires are inspected at the site at regular intervals to ensure that there is no slackness present in the installation. An installation crew of 3 men erected the measurement mast. This process took approximately 5 hours to complete. All of the measurement instruments have been calibrated by the manufacturer. The anemometer measures the wind speed, while the wind vane measures the wind direction. The anemometer is an NRG # 40C model, which is one of the most common anemometers in use today for small-scale wind measurement applications. It consists of a simple light, plastic construction with 3 cups, with a Teflon bearing system for ease of rotation. The wind vane is an NRG #200P model, which is mounted to measure the wind direction. The datalogger records the signals from the four wind sensors and produces outputs in the form of wind speed and direction values. The Nomad also comes with desktop software, which could produce graphs such as wind rose graphs, power curve graphs, wind distribution graphs, time series graphs, diurnal graphs, X-Y graphs and, finally, expected energy reports. Only the wind rose capability will be used here.

The data collected is compared with other regionally collected data, at the main W.I.T. Cork road campus in Waterford and also off the West coast of Ireland from the M6 Buoy at sea. In one suit of B+L recorded data there appeared to be a period of lulls, which lasted for approximately one and a half months. However, by comparing with other wind data and national wind generated output over the same period, it became obvious that there was a glitch in the measurement system, resulting in the recording of consecutive zero wind speed values. This was traced to a faulty flashcard in the data logger and was remedied by replacing the flashcard.

3.3 Wind speed distributions

The Weibull distribution was so called after Waloddi Weibull in 1951. It has many varied applications; however, more recently it has focused on wind energy.

The Weibull wind speed probability density function, $P_{(v)}$, can be described in the following format:

$$P = \frac{k}{v}\left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\}$$

where $P_{(v)}$ is the probability of the occurrence of a particular wind speed v.

c is the scale factor, the units of which are in m/s.

k is the shape factor, which is dimensionless.

This two-parameter Weibull distribution has a cumulative distribution function given by:

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

The mean and variance of the 2-parameter Weibull distribution are given by the following expressions:

$$\langle \mathrm{v} \rangle = \mathrm{c}\,\Gamma\left(1+\frac{1}{\mathrm{k}}\right)$$

$$\sigma^2 = c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma\left(1+\frac{1}{k}\right)\right]$$

where Γ is the gamma function.

3.3.1 Extracting the two parameters, *k* and *c*, from a data set

The Weibull shape and scale parameters *k* and *c* can be determined from Weibull distributed measured data using the natural log method, which will be described next.

If the wind speed distribution is actually Weibull, then the CDF, *F(v)*, may also be written as

$$F(v) = 1 - e^{-(m)}$$

$where\ m = \left(\frac{v}{c}\right)^k$ $and\ c\ and\ k\ are\ the\ Weibull\ shape\ parameters$

Given that *k* and *c* are what need to be found out, it's necessary to manipulate the expression above:

$$\ln\left(1 - F(v)\right) = \ln(e^{-m}) = -m = -\left(\frac{v}{c}\right)^k$$

And:

$$-\ln\left(1 - F(v) = \left(\frac{v}{c}\right)^k\right.$$

And further manipulation gives:

$$ln[-\ln\left(1 - F(v)\right] = ln\left(\frac{v}{c}\right)^k = kln\left(\frac{v}{c}\right) = kln(v) - kln(c)$$

which is of the form *y=mx+c*

This equation is now a linear expression in *ln*(*v*). As it is linear it can be used to find *k* (slope of the line) and *c* using manipulation or the intercept point of the LHS versus *ln(v)*. This technique was used extensively to calculate *k* and *c* and results of this analysis will be presented in a sample calculation in Chapter 4.

3.4 Power in wind

In this paragraph the relationship between the wind speed and the power in the wind is derived. Consider a flow of air of constant speed *v*, passing through a small area *A* perpendicular to the wind direction, see Figure 19. Assume that the speed of the wind does not vary over the small area *A*. Let the length of the cylinder be *vdt*, so that in a time *dt* all the air contained in this volume passes through *A*.

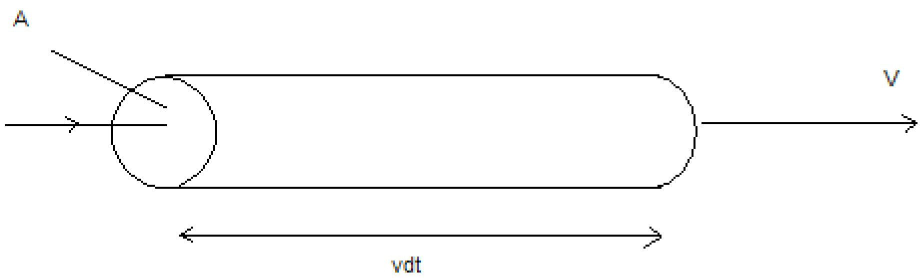


Figure 19 Illustration of power calculation contained in a wind of constant speed *v*

If the mass of the air contained in this volume element is *dm* then

$$\mathrm{dm} = \rho dV = \rho v dt A$$

where density of the wind is ρ.

The kinetic energy of this mass is *dE* and this energy passes through the area A in dt seconds so that the power (*P*) is given by

$$P = \frac{dE}{dt}$$

$$\begin{aligned} dE &= Pdt \\ &= \frac{1}{2} dm\, v^2 \\ &= \frac{1}{2} \rho v A dt\, v^2 \\ &= \frac{1}{2} \rho A v^3\, dt \end{aligned}$$

Therefore the power of the wind is

$$P = \frac{dE}{dt} = \frac{1}{2}\rho A v^3$$

In the context of a wind turbine, *A* is the swept area and is equal to πr^2, where *r* is the length of the blades.

To optimise the power available at a wind turbine, the site should have a large average annual wind speed and the swept area should be as large as economically viable.

Due to the cubic relationship that exists between wind speed *v* and wind power, small variations in wind speed lead to large fluctuations in wind power. These large fluctuations present a problem to existing national grids in most countries. Thus modern national grid infrastructures need to be able to cope with the larger power contribution coming from the ever-increasing size and number of wind turbine developments.

Estimating the available energy from the wind annually

If the power was recorded continuously and the graph of *P* versus *t* was continuously smooth then the energy available from the wind is:

$$E = \int_0^T P(t)dt.$$

Now if $P = C_p \frac{1}{2}\rho A v^3$ then

$$E = \int_0^T C_p \frac{1}{2}\rho A v(t)^3 dt$$

$$= \frac{1}{2} C_p \ \rho \ A \int_0^T \left(v(t)\right)^3 dt$$

$$= \frac{1}{2} C_p \rho A T \left\langle v^3 \right\rangle = \frac{1}{2} C_p \rho A T \left\langle v_{ref}{}^3 \ \frac{h^{3\alpha}}{h^{3\alpha}{}_{ref}} \right\rangle$$

$$= \frac{1}{2} \frac{C_p \rho A T v_{ref}{}^{3\alpha}}{h_{ref}{}^{3\alpha}} h^{3\alpha} \left\langle v_{ref}{}^{3\alpha} \right\rangle$$

where $\left\langle v^3(t)\right\rangle_T$ is the time average of the cube of the wind speed, and

T =1 year in this case.

It is assumed that $\left\langle v^3(t)\right\rangle_T$ is equal to the average of the cube of the velocity obtained from a Weibull distribution of wind speed. V~w/k,c. Therefore the average of the cube is given by:

$$\left\langle v^3(t)\right\rangle_T = \left\langle v^3\right\rangle = c^3\left(1+\frac{3}{k}\right)$$

$$\therefore E = \frac{1}{2}\rho ATC_p C^3\Gamma\left(1+\frac{3}{k}\right)\frac{h^{3\alpha}}{h_{ref}^{\;3\alpha}}$$

$$Energy density\frac{E}{A} = \frac{1}{2}\rho TC_P C^3\Gamma\left(1+\frac{3}{k}\right)\left(\frac{h}{h_{ref}}\right)^{3\alpha}$$

Variation of air density with temperature and pressure

Assume that air is an ideal gas i.e. it obeys the ideal gas law.

$$PV = NKT \therefore P = \frac{Nm}{V}\cdot\frac{kT}{m} = \rho\cdot\frac{kT}{m} \therefore \rho = \frac{mP}{kT}$$

where *m* is the average mass of a ‘molecule’ of air, *P* is the air pressure, *T* is the temperature of the air and *k* is Boltzmanns’s constant.

The power co-efficient C_p

A wind turbine can only extract a fraction of the energy in the wind. Betz proved that the maximum power extracted from the wind is:

$$P_{Betz} = \frac{8}{27}\rho Av^3$$

$$C_p = \frac{power\ extracted\ from\ the\ wind}{power\ available\ from\ the\ wind} = \frac{P_{extracted}}{P_{available}}$$

The extracted power is given by

$$P_{extracted} = C_p P_{available} = C_p \cdot \frac{\rho A v^3}{2}$$

The maximum power coefficient (Betz limit)

The power coefficient for any converter is the ratio of the maximum power extracted to the power available. In essence, in the case of wind, not all of the wind is captured by turbine blades.

The maximum value of the power coefficient is called the *Betz limit*.

$$C_{p\,\max} = \frac{\max imum\ power\ extracted}{power\ available} = \frac{\frac{8}{27}\rho A v^3}{\frac{1}{2}\rho A v^3} = \frac{16}{27} = 0.5926$$

The maximum power that can be extracted is 59% of that in the wind.

Derivation of Betz limit

The rate at which *m* passed through an area *A* is given by

$$\frac{dm}{dt} = \rho v A$$

The diagram shows the wind of speed v_1 passing through an area A_1 far away from the wind turbine. The wind turbine with swept area *A* reduces the speed at the plane of the rotor to *v*. The speed of the air is further reduced to v_2 as it crosses A_2 far removed from the turbine. It is slowed because it pushes the air behind the rotor out of the way. From the conservation of mass

$$\rho v_1 A_1 = \rho v A = \rho v_2 A_2 = constant$$

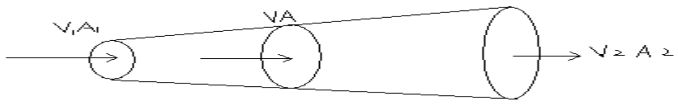


Figure 20 Illustration of Betz limit derivation

Before the turbine affects the wind it has velocity v_1, its power is P_{in}. When the wind passes through the turbine it eventually has a lower constant velocity and its power is P_{out}. The power extracted from the wind, P_t, is equal to the difference between P_{in} and P_{out}.

$$P_t = P_{in} - P_{out}$$

$$= \frac{1}{2}\frac{dm}{dt}v_1^2 - \frac{1}{2}\frac{dm}{dt}v_2^2$$

$$= \frac{1}{2}\frac{dm}{dt}\left(v_1^2 - v_2^2\right)$$

Using the average of v_1 and v_2 to find the wind at the turbine

$$\frac{dm}{dt} = \rho v A = \rho\left(\frac{v_1 + v_2}{2}\right)A$$

The power extracted is therefore

$$P_t = \frac{1}{4}\rho A\left(v_1 + v_2\right)\left(v_1^2 - v_2^2\right)$$

Let the power of the wind passing through A, without the turbine present be P_o.

$$P_o = \frac{1}{2}\rho A v_1^3$$

Note the speed used is v_1 as this would be the speed when the turbine is not there. The power co-efficient C_p is

$$C_p = \frac{Pt}{Po} = \frac{1}{2}\left(1+\frac{v_2}{v_1}\right)\left[1-\left(\frac{v_2}{v_1}\right)^2\right]$$

Note C_p is a function of $\frac{v_2}{v_1}$. Let $x = \frac{v_2}{v_1}$. Note $0<x<1$

C_p is written in terms of x as follows.

$$C_p = \frac{P_t}{P_o} = \frac{1}{2}(1+x)[1-x^2]$$

It must now be determined what value of x maximises the value of C_p. Differentiating C_p and setting the derivative equal to zero gives a quadratic equation. The only positive root is $x = \frac{1}{3}$. The second derivative of C_p is negative for this value indicating the C_p is maximised when substituting $x = \frac{1}{3}$. As mentioned earlier, the maximum value of C_p is

C_p, Betz = 59.3% of overall power.

Conclusion: If the wind turbine slows the air down to one third of its initial speed, the theoretical maximum power extracted from the wind, is approximately 60% of the energy available in the wind.

3.5 Analysis methods

3.5.1 Use of the Weibull distribution and wind site analysis

One of the primary areas of concern that needs to be addressed prior to the development phase of a wind energy installation project is whether the proposed site is exposed to winds of sufficient velocity to make the final project sustainable. In any wind energy development project, the first phase in the project plan is the site selection process. In the case of this study; the site identified is the Bausch & Lomb Waterford manufacturing facility, with a view to installing a single auto-producing turbine to feed part of the facility's energy requirement.

Wind data for sites in the site selection process/phase is usually an approximation taken from the national Wind Atlas or wind-monitoring stations in the vicinity or region of the site. Apart from whether a potential site displays promising wind speeds, there are also a number of other factors, which need to be taken into account. Such factors include: proximity to existing infrastructure for possible electrical grid connections, any potential obstacles such as buildings or the local terrain, the challenges of the planning process and also financial constraints. From a financial perspective, a wind site, which exhibits average wind speed values of between 6 and 8m/s at a height of 50m, would be considered as a suitable site to implement a standalone wind turbine development project (Twomey 2006). For an autoproduction site, the average windspeeds can be lower, as the value per kW-hr is higher, since displaced purchased electrical energy is of higher price than energy sold to the grid. Once a provisional, desk-based decision has been reached with regards to site selection, real-time monitoring of the site is required. Real-time monitoring is over a minimum period of 6 months (in order to build up an adequate bank of data), although ideally over a full 12-month period, with the period benchmarked against the 30-year Met Eireann averages from the nearest monitoring station, which is the best mechanism to understand whether the monitoring regime happened in a particularly windy (or vice versa, calm) 12-month period. The real-time monitoring phase of the chosen site will involve erecting a wind monitoring mast, the height of which would ideally be as close to the height of the final wind turbine installation as possible, to ensure the best possible accuracy. In some cases however it is neither practical nor financially viable to have a monitoring mast height close the hub height of the installed turbine as some modern proposed developments contain turbine hub heights of in excess of 100m. The vast majority of current winds monitoring masts are of the order of 50m in height, with a scaling law applied to the data to provide estimations of what the actual hub height wind speed would look like. A series of anemometers and wind vanes would be located along the height of the mast to measure both wind speed and direction. Financial and practical constraints meant that the scope of this project was limited to the installation of a 10m-wind mast at the site. The real-time site wind-monitoring phase usually lasts 12 months. If wind as an energy source were non-variable, there would be no need for prediction and characterization modelling.

The variability which is inherent in wind is best described and characterised by a probability distribution function, drawn from a measurement regime. The probability distribution that usually best describes wind speed/energy patterns is the Weibull distribution (Gupta *et al* 2010). The Weibull distribution is typically characterized by two main parameters, the *k* parameter and the *c* parameter. The *k* parameter is known as the shape parameter and it describes the shape of the distribution. Higher values of *k* would indicate more of a spike, or concentration of speed, in the distribution. The *c* parameter is known as the scale parameter and describes the area under the Weibull distribution graph; higher values of *c* indicate a more spread out graph while lower values of *c* indicate a less spread out graph. A site exhibiting high values of *k* and *c* tends to contain higher wind speed values and is more suitable for a wind turbine installation project, in comparison with a site with lower values of *k* and *c*.

The Weibull distribution characteristics can be excellently analysed using the *R* software programming language. In the graphs in Figure 21 and Figure 22 software was written using *R* whereby the *k* and *c* parameters have been swept in order to more accurately understand the effect of changing each has on the overall Weibull distribution. Figure 21 has the shape parameter *k* fixed at 1.8, and *c* is swept up to 8 m/s in steps of 2 m/s. As the value of *c* increases, so does the area under the Weibull distribution graph, as the base widens. Moreover, as the base gets wider, the peak of the distribution lowers.

The Weibull distribution can be described by using the following notation, if the wind speed, *v*, has a Weibull distribution with shape parameter, *k*, and scale parameter, c, then the probability function for the wind speed is given by the following:

$$F(v) = P(V<v) = 1 - e^{-(\frac{v}{c})^k}$$

and the probability density function f(*v*) is the derivative of F(*v*)

$$f(v) = \frac{dF(v)}{dt}$$

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

An important notation is *v~w(k, c),* note *c* has the same units as *v.*

A proposed wind measurement site can be accurately characterised by the resultant *k* and *c* parameters that it produces. The Weibull shape parameter *k* generally ranges from 1.5 to 3.0 for most wind regimes, while the *c* value generally ranges from 2 m/s to 6m/s and in some instances 8m/s (Waewsak *et al* 2011).

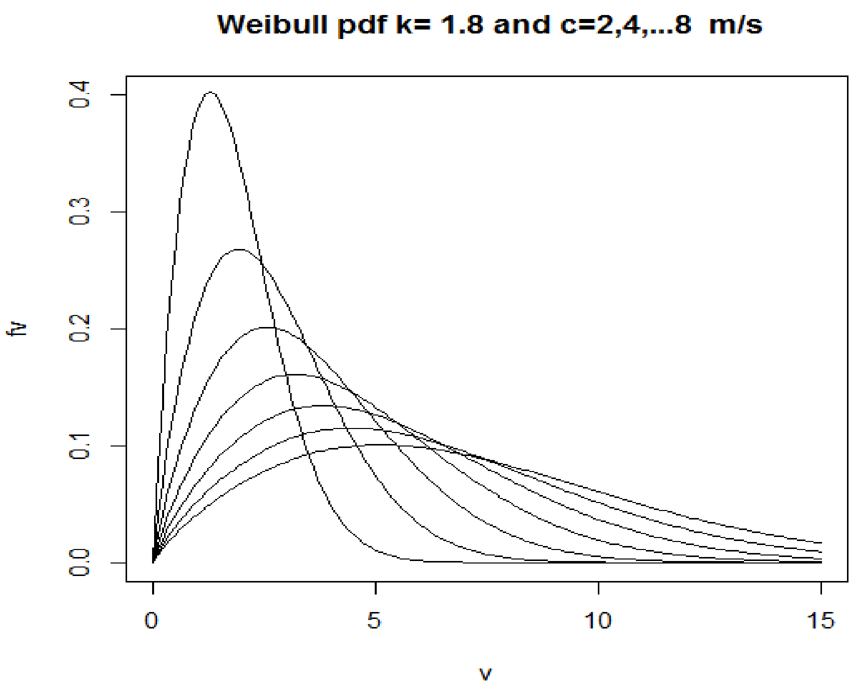


Figure 21 Weibull characteristics for fixed *k* value

Here, *k* is designated as 1.8, which was calculated as the 36-month average value for the shape factor. Typically wind feasibility studies for proposed wind development sites that exhibit low *k* and *c* values tend to contain lower average wind speeds and are less favourable for wind turbine developments. Coastal locations or measurement stations out at sea tend to exhibit *c* values which are higher than those exhibited by inland non coastal regions, the 36 month average for the M6 Buoy at sea was 2.29. Thus a proposed wind development site, can readily be characterised by Weibull shape parameters *k* and *c.*

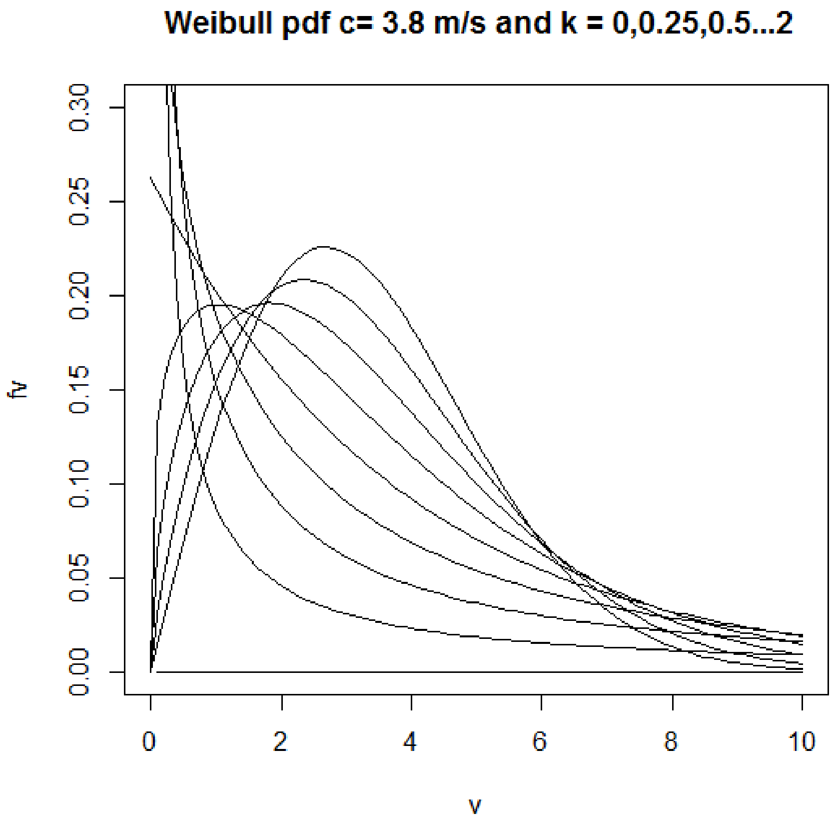


Figure 22 Weibull characteristics for fixed *c* value

Figure 22 depicts a graph of f(*v*) versus *v* for a fixed *c* value of 3.8. Here *c* is 3.8, which reflects the 36-month average value for the scale factor for the measured data from the Bausch + Lomb manufacturing facility in Waterford. The scale factor *c* is fixed, while the shape factor *k* is variable, in this instance, the *k* value is graduated in steps of 0.25 from a minimum of 0 to a maximum of 2. It is clearly apparent that as the value of *k* increases, the base or the area under the Weibull distribution decreases.

3.5.2 Shadowing effect and the Weibull spike

As mentioned previously, there are two common techniques, which exist for the viability assessment of a proposed wind energy converter auto-production project. One technique involves the desk-based analysis of the long-term averaged wind speed for that site. Long-term average wind speed data is mapped for most countries and permit estimates for the locality of the proposed project.

A second more elaborate and more expensive technique entails erecting a wind monitoring mast. Depending on the size of the proposed auto-production unit, this expense may preclude the monitoring mast, the decision on the possible installation of a small domestic wind turbine being an obvious example. Also related to the proposed unit size is the actual monitoring height. In Ireland for example, certain planning permission waivers exist for hub heights of less than 10m (domestic) or 20m (commercial, agricultural, industry) leading to the erection of monitoring masts of 6-10m in height (IWEA 2013). At such heights, the risk of wind shadowing, causing unusually large low or zero wind speed readings is also a risk.

Both the desk-based wind atlas estimation and also the wind shadowing effect can lead to overestimations of the power potential of a given site. The shadowing effect will manifest itself as a typically short sharp spike in the Weibull analysis for a site as shown in Figure 23, and will follow the normal Weibull distribution there after. The shadowing is outlined in Figure 23 below as the spike at low values in the distribution, followed by the more typical shape of a site's wind distribution.

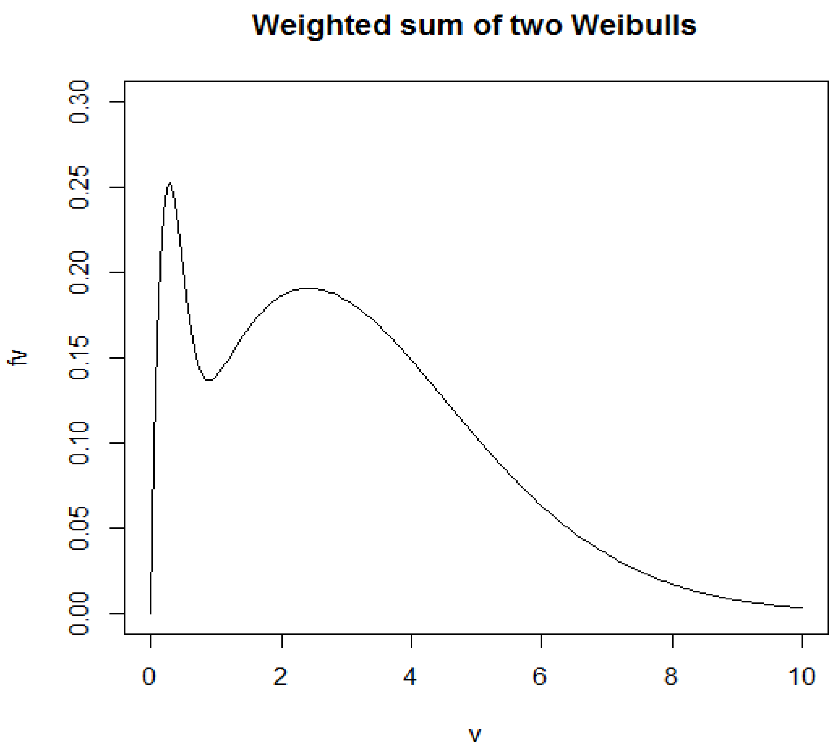


Figure 23 Weibull spike and shadowing effect

3.5.3 Weibull results

There are a number of distributions, which exist, in order to try and effectively describe as accurately as possible the wind speed distribution, namely the Weibull and the closely related Rayleigh distribution (occurs when k =2), as well as the lognormal and Frechet distributions. The Weibull distribution is one of the most common and widely accepted distributions.

An interesting observation to note with the Weibull distribution obtained for the B + L site over one month in the year 2010, is the presence of the initial spike in the data, whereby approximately 260 data points were counted below 1m/s. A straightforward Weibull distribution as has been previously described could be created for this data and used as the basis for analysis, *if the spike is ignored*. As there were approximately 4,000 data points collected for the month, then the spike represents 6.5% percent of the data. Consequently, any simple Weibull based analysis that ignores the initial spike, will be an assumption (as the complete distribution is NOT a Weibull distribution) and also will lead to an overestimation of power, as this percentage of readings will be ignored. Moreover, in general for all wind mast distributions, as turbine cut-in speeds are usually over 3m/s, the useful power distribution will of course also not be a simple Weibull distribution.

For k values up to and also exceeding 2, the Weibull distribution is an accurate means of modelling the Weibull distribution, for a k value equal to 2, the Rayleigh distribution is utilised.

3.5.4 Cube of mean versus mean of cube

It was mentioned in Section 3.5.2 that desk-based wind turbine site feasibility studies are also at risk of error, as they tend to rely on the long-term mean wind speeds for the site. However, wind power is a function of wind speed *cubed*. For any parameter's distribution there is a difference between the cube of the mean and the mean of the cube for most of the possible values the parameter can take.

where P = power generated
ρ = Air density
v = Wind speed velocity

The equation given above describes the power in a wind of cross-sectional area, A.

The equation shown below describes the ratio of the mean of the cube versus the cube of the mean. This ratio, *f*, is also known as the Energy Pattern Factor.

$$\langle v^n \rangle = c^n \Gamma\left(1 + \frac{n}{k}\right) \quad n = 0, 1, 2, \ldots$$

$$\frac{\langle v^3 \rangle}{\langle v \rangle^3} = f = \frac{c^3 \Gamma\left(1 + \frac{3}{k}\right)}{c^3 \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^3} = \frac{\Gamma\left(1 + \frac{3}{k}\right)}{\left(\Gamma\left(1 + \frac{1}{k}\right)\right)^3}$$

(Sanusi, YK *et al* 2011)

The following *R*-code can be used to visualise the relationship between the Energy Pattern Factor, *f*, and the Weibull shape factor, *k*.

```
k=seq(1,6,0.1)
f=gamma(1+3/k)/gamma(1+1/k)^3
plot(k,f,type='l',ylim=c(0,6),xlim=c(0,6),main="Energy pattern factor, f, versus k")
abline(h=1, lty=2)
abline(v=1, lty=2)
```

R plots this ratio in Figure 24. A horizontal line has been added to show an asymptote for *f*, as *k* goes to infinity. A vertical line has also been added at *k*=1, as it may be recalled from Figure 21, that values of *k* below this number correspond to sites where all wind speeds are at or very near zero. Notice that only if the Weibull shape factor, *k*, approaches 5, is the cube of the mean approximately equal the mean of the cube. When *k*=2, as is approximately the case for the B+L site, taking the mean wind speed and using it to estimate the site's wind power would lead to an underestimate by a factor of 1.9 times.

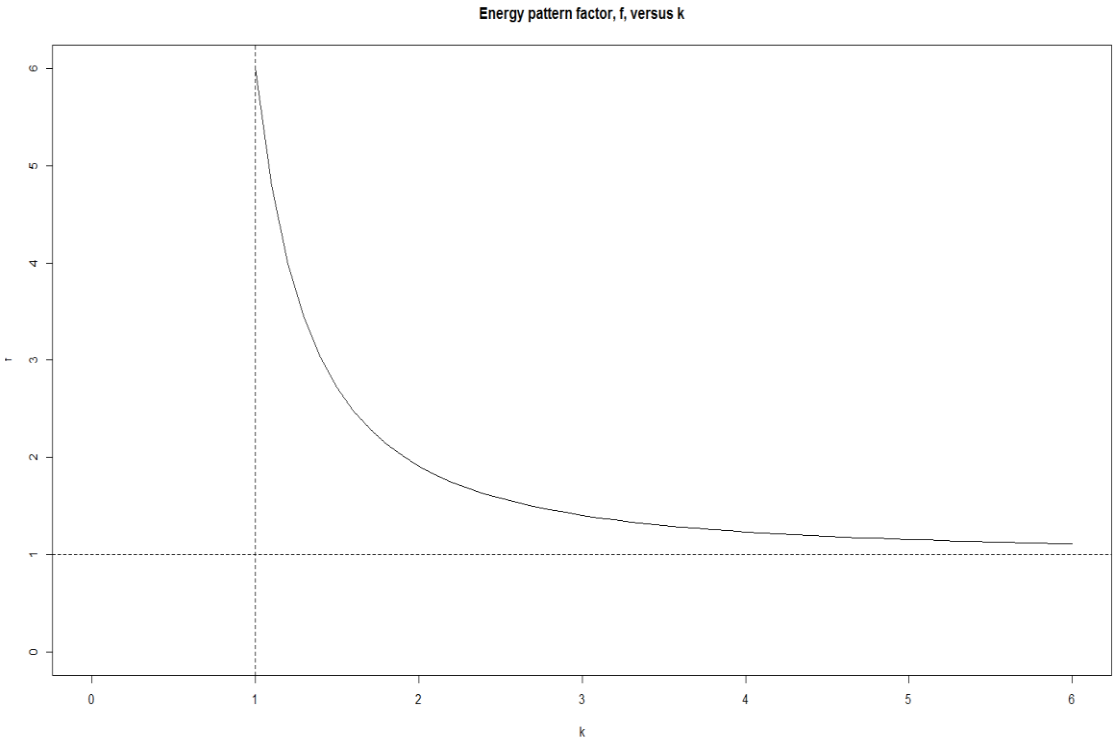


Figure 24 Energy pattern factor *f*, versus *k*

Errors in such assumptions can lead to large discrepancies in power generation calculations and the size of the error depends entirely on the *k* value, if the wind distribution at the chosen site may be modelled by a Weibull distribution. Figure 25 shows a typical example of how the shape of a typical Weibull distribution matches that of a typical wind speed distribution.

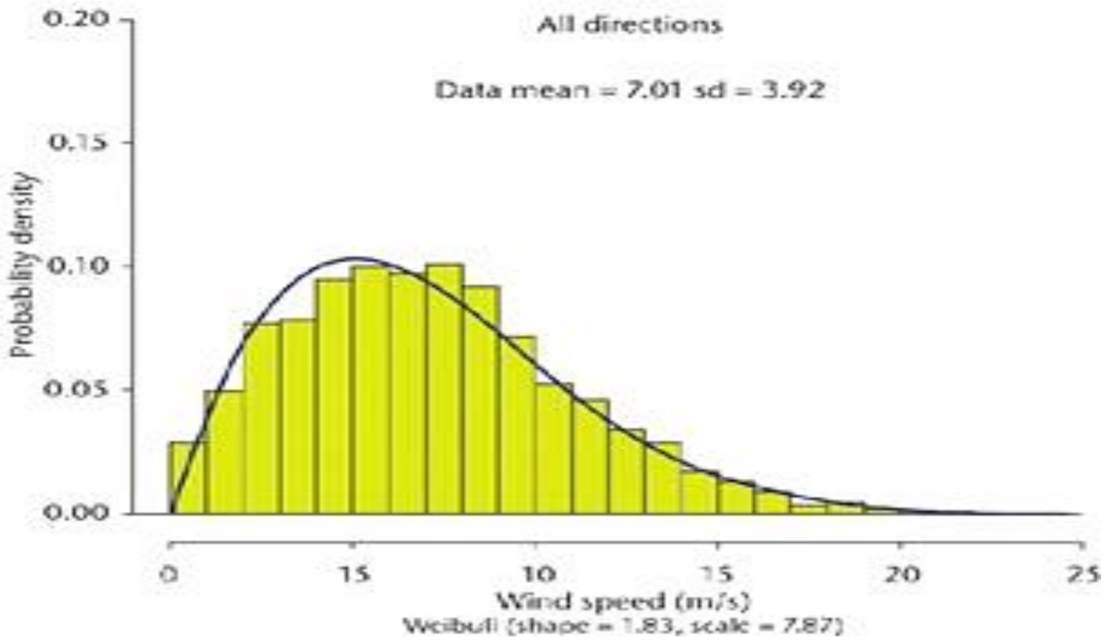


Figure 25 Typical Weibull windspeed distribution (Metoffice 2012)

3.5.5 Rayleigh distribution

For the Rayleigh distribution to work on a data set, whose distribution approximates a Weibull, *k* must equal 2; otherwise the distribution is the more general Weibull. The Rayleigh distribution is related to the Weibull distribution and the distribution is named after Lord Rayleigh.

The Rayleigh distribution function is defined as follows:

$$F(u) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{u}{\bar{u}}\right)^2\right]$$

where,

u = velocity

$\bar{u}$ = mean velocity

π = 3.14

k = Shape parameter (which equals 2)

The Rayleigh distribution is shown in Figure 26 for July 2010. The Rayleigh distribution was applied to the month of July, as a consequence of data analysis returning a *k* value of 2 when the Weibull shape parameters were calculated for that month. The series one values represent the measured data for the Bausch + Lomb site, while the series 2 data represents the fitted Rayleigh distribution. The Rayleigh distribution represents a close fit for the data for *k*=2 for the month.

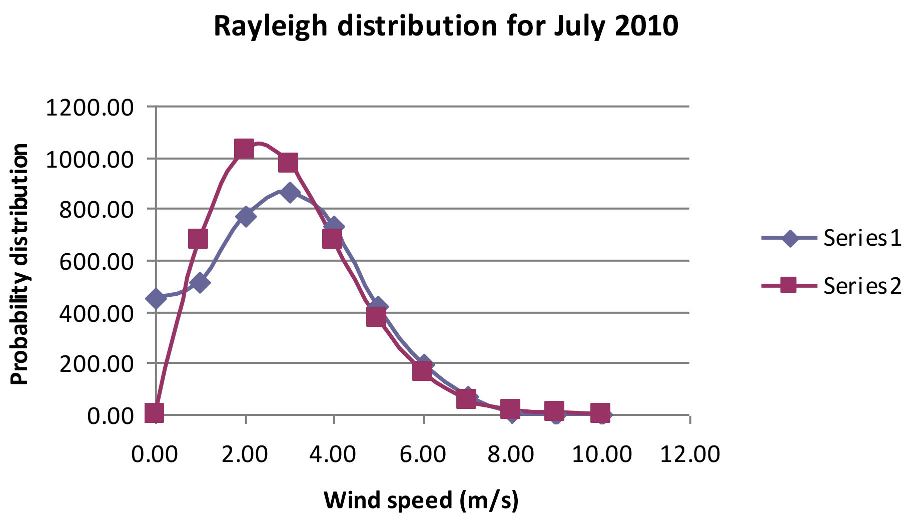


Figure 26 Rayleigh distribution for July 2010

3.5.6 Chi – squared goodness of fit test

The Chi square goodness of fit test is used to assess how well the experimentally observed distribution matches the theoretically predicted distribution. The Chi square test is denoted by the following equation given below.

$$x^2 = \Sigma \frac{(O_i - E_i)^2}{E_i}$$

Where

Σ = Sum of the values.

Observed (O_i) = source data gathered/obtained

Expected (E_i) = data generated from ideal model

A Chi square goodness of fit result of zero or close to zero would indicate a good closeness of fit of the data.

3.5.7 Matching a wind turbine manufacturer to the wind data obtained

A 12-month time period in 2010 was analysed in terms of wind speed produced. The power curve for a Vestas V47 wind turbine was used as a test case to estimate power production. The Vestas V47 usually has a hub height of 47m and a rated capacity of 660kW. The cut in speed for this turbine is 4m/s and the cut-out speed is 25m/s. The published wind turbine data were combined with the wind site data in an attempt to estimate the wind turbine power output for that site.

The first step in the process was to obtain the wind power profile data for the Vestas V47 wind turbine and plot the wind turbine power curve from this data. Illustrated in Figure 27 is the wind turbine power curve. The cubic relationship between power and wind speed can be seen after cut-in and before the protective plateau region, roughly in the section between wind speeds of 4 to 0m/s.

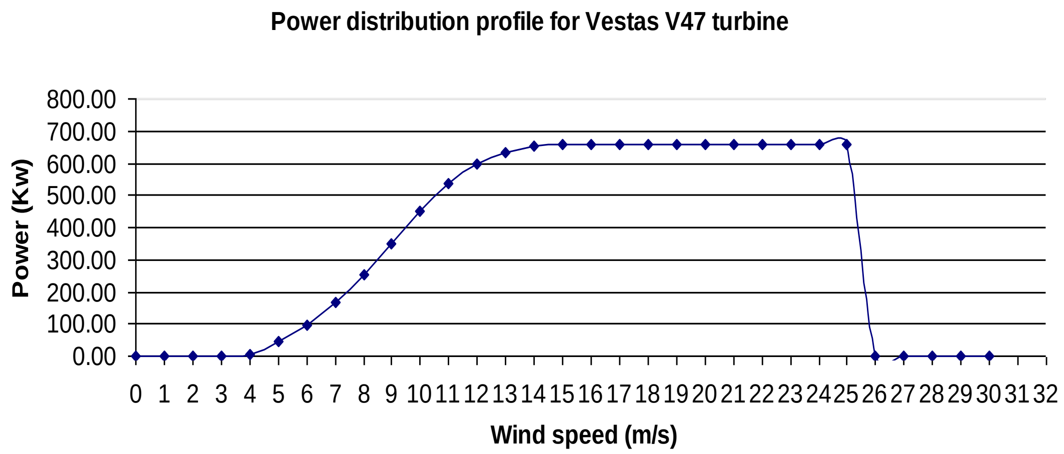


Figure 27 Wind power curve for the Vestas V47 wind turbine

The wind turbine power curve will identify for the range of wind speeds what the expected power output of the turbine will be.

The Weibull distribution for the measurement site is then compared with the published wind power curve from the turbine manufacturer. The Weibull distribution for the site will identify how many wind speed values will fall below the useful cut in speed for the identified wind turbine and also how many wind speed values will fall outside of the cut-out speed of the wind turbine. Successful matching of the manufacturers wind turbine power curve to the site Weibull distribution is key in the turbine selection process.

The energy output along with the power output is then calculated for the measurement site. The wind speed velocities at the site are scaled up to the hub height of the wind turbine of interest, the scaled up wind velocities are then cubed. The energy output is then calculated according the energy output formula given in section 3.4 taking in to account the swept area of the wind turbine blades. The power output for the site is subsequently calculated by multiplying the energy output by C_p.

3.5.8 Wind variation with height

The wind data collection system installed at the Bausch + Lomb Waterford site has a main limiting factor associated with it, and that is that the maximum measurement height of the sensors is 10m (with sensors at 6m also). The hub height of the majority of current commercial wind turbines will be a multiple of this, typically in the region of 40 – 50m in height (IWEA 2013). There are wind measurement masts currently on the market which are as high as 60m, however due to project financial constraints, a 10m mast was chosen for this suite of measurements.

3.5.9 Scaling up

The Weibull distribution for the site for the 12-month period was also computed.

The wind speed data measured at 10m was then scaled up to the predicted hub height of 47m for the Vestas V47 turbine using the $\frac{1}{7}$ power law and the scaling law equation. The wind speed values obtained using the $\frac{1}{7}$ power law were used, as the results produced from the scaling law equation were much higher than the published regional values from the SEAI. The scaled up values are given in chapter 4. These new wind-speeds are assumed to have the same frequency distribution as the 10m measured wind speeds, which is of course a conservative estimate, due to the wind shear mentioned in Chapter 2.

In order to scale up the wind speed values at 10m, two different approaches were examined which were using the $\frac{1}{7}$ power law and the scaling equation. The $\frac{1}{7}$ power law can be described as follows:

$$\frac{v}{v_{ref}} = \left(\frac{h}{h_{ref}}\right)^{\alpha} \quad \text{Where, } \alpha = \frac{1}{7}$$

While the scaling equation can be described as follows:

$$\frac{v_2}{v_1} = \frac{\ln\left(\frac{h_2 - d}{z_0}\right)}{\ln\left(\frac{h_1 - d}{z_0}\right)}$$

In the case of the scaling equation, α = Helman exponent or surface roughness factor.

It is interesting to note that the scaling law approach produced wind speed values scaled up to 47m that were approximately double the $\frac{1}{7}$ power law values. The average wind speed at a scaled up height of 47m using the scaling equation was 8.544 m/s, while the average using the $\frac{1}{7}$ power law was 4.217 m/s. In both cases, these were the annual averages for 2010. The $\frac{1}{7}$ power law values were used for all further calculations, as it was felt that these values were more consistent with the site, as the Helman exponent calculated for the scaling equation, was at best an approximation, and would have had a significant effect on the final values.

The Helman exponent or surface roughness factor can vary greatly from site to site. This depends largely on the type of terrain that the wind measurement mast is situated on. For typically flat and plain landscapes the surface roughness factor equates to 0.1, while for urban environments such as towns and cities, it can be as much as 2.0. An accurate approximation for the site in which this project is concerned with would be 0.6; however that is an approximation, as opposed to a more exact figure.

As mentioned above, the height of the site wind data collection/measurement system is a limiting factor, as the wind speed varies with varying height as the $\frac{1}{7}$ power law and scaling equation have shown. The speed of the wind tends to increase with greater height above ground, as there is decreased surface friction above ground level, and there are fewer restrictions to greater airflow at higher altitudes. As a consequence of this fact, wind turbine hub heights are becoming ever higher to take advantage of these greater wind speeds and thus generate larger amounts of electrical power output as a result. In the case of the Vestas V47 wind turbine with a rotor diameter of 47m, based on calculations, for different locations along the rotor blade, power output variations exist, due to the varying scale up wind speeds at those locations. At a hub height of 47m, the lower tip of the rotor is at 23.5m and produces on average 140kW, while for the upper tip of the rotor at a height of 70.5m, the average power output is 229 kW, while at 58.75m, halfway along the span of the upper rotor, a value of 209kw is produced.

4.0 Data results Site analysis

4.1 Bausch + Lomb site characteristics

The wind measurement site is situated at the Bausch + Lomb manufacturing facility located in the IDA industrial estate in Waterford city. The wind monitor and vane are indicated by a red dot on the site plan (shown in Figure 28) and is situated to the west of the manufacturing facility on the edge of the main car park.

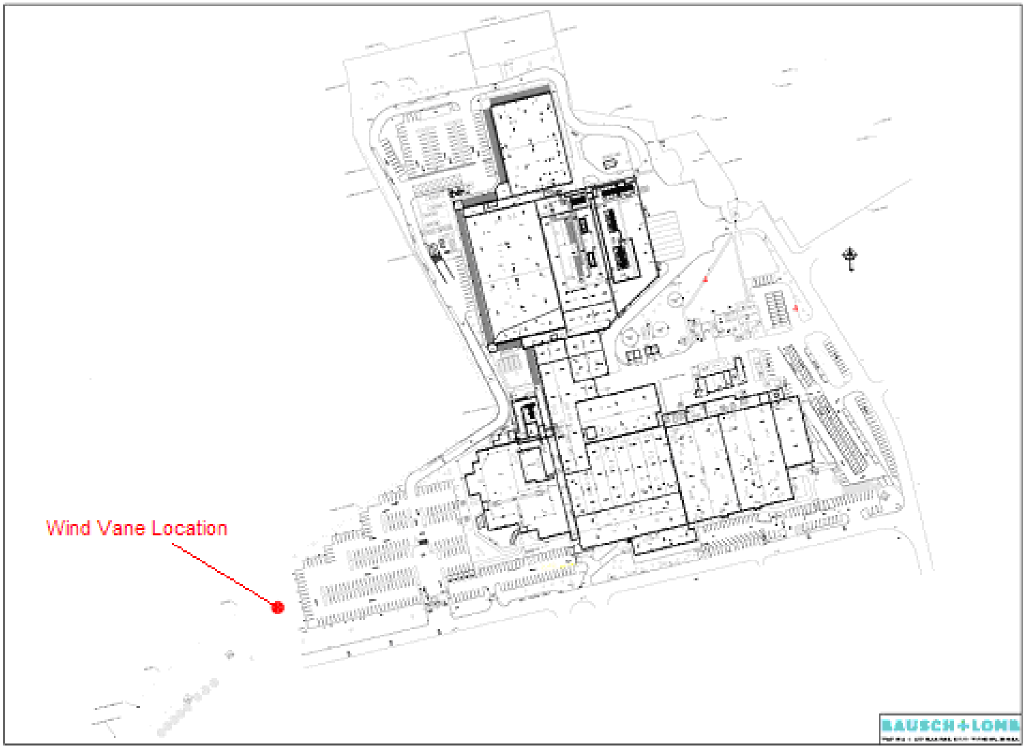


Figure 28 Site layout of the overall Bausch + Lomb manufacturing facility and wind vane location

Prior to any wind turbine installation development project an understanding of the wind patterns at a given site is of major importance, as planners and project teams need to be armed with this information initially to decide whether or not a site is feasible, to position the turbine in the most advantageous position, to estimate the annual and monthly power output, as well as the variability in that supply. A good monitoring and analysis regime can provide this information before the construction phase.

This approach was also taken in this work, albeit, not at a commercial level, given that the mast is relatively low at 10m and that the measurement period is unusually long at 36-months.

For the measurement site at Bausch + Lomb, wind data was collected at this site over a three-year period. Over the monitoring period, the mean wind speeds at heights of 6m and 10m respectively were found to be 2.51 m/s and 3.21 m/s. The data was primarily analysed using the two-parameter Weibull distribution function. The two parameters in question were *k* the shape factor and *c* the scale factor.

The wind speed data obtained from this site compares favourably with some local estimates, but seems relatively low compared with others. For the year 2011, the average site wind speed was scaled up to a height of 47m and found to be 4.22 m/s. Met Éireann indicate that at a measurement height of 50m, average windspeeds for the South-East region are approximately 5m/s, whereas from the SEAI wind atlas (Figure 29), windspeeds are estimated to be between 6.5 – 7.0 m/s at that site. Given the cubic relationship between wind speed and power, a commercial venture would at this point require 50m monitoring mast to remove this doubt and provide accurate wind speed data and statistics for that height.

The wind speed and direction values were recorded at intervals of 10 minutes. This level of data resolution equated to 157,680 data points being collected over this 3-year period.

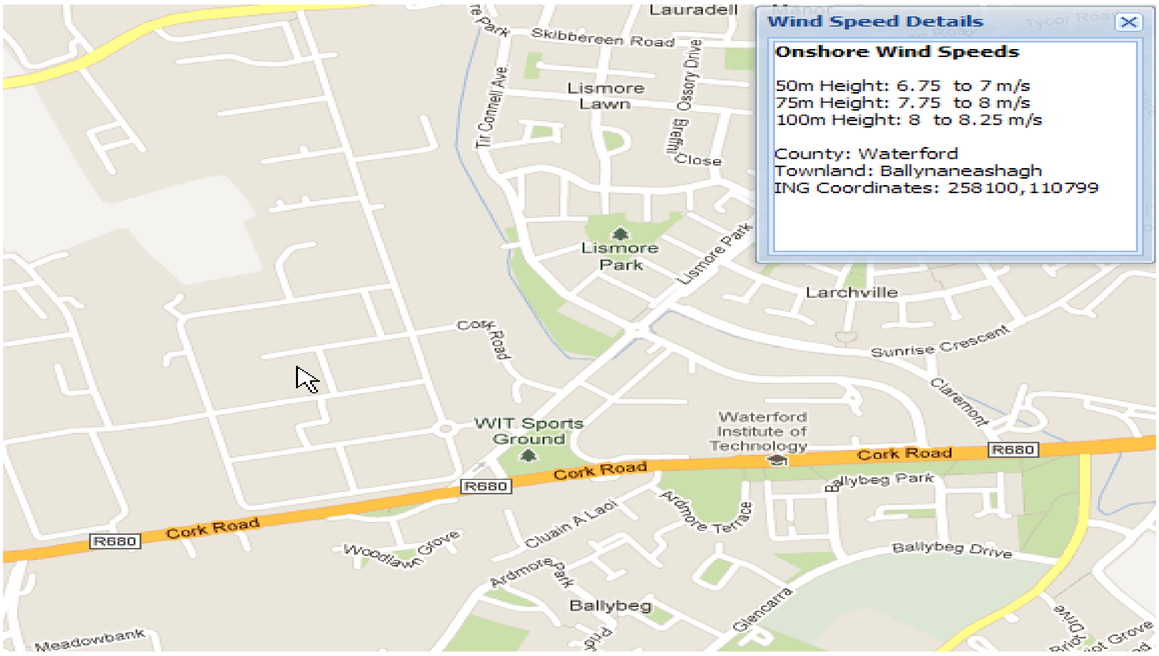


Figure 29 SEAI. (2012). Wind speed data for Waterford city from SEAI *Wind atlas.*

Table 1 shows the 2009 average wind speeds for each month of the year along with standard deviations at heights of 6m and 10m. The annual average wind speed and standard deviation for the year are also displayed.

Years	2009			
Parameters	**V(m/s) @6m**	**σ @ 6m**	**V(m/s) @10m**	**σ @ 10m**
January	3.51	2.18	4.28	1.48
February	2.30	1.64	2.90	1.89
March	3.50	2.06	4.34	2.37
April	2.56	1.55	3.30	1.86
May	3.36	1.70	4.08	1.95
June	2.28	1.33	2.80	1.51
July	2.62	1.54	3.31	1.76
August	2.72	1.40	3.51	1.70
September	3.03	1.29	3.98	1.63
October	3.03	0.41	3.98	0.55
November	2.05	1.10	2.45	1.30
December	2.55	2.02	3.11	2.33
Annual Average	2.79	1.51	3.50	1.69

Table 1 2009 average wind speeds and standard deviations from January to December

In Figure 30, a 12-month box plot (box and whisker plot) representation for 2011 is drawn for month-to-month variation in wind speed values at a measurement height of 10m. A box plot makes no assumption in terms of the data distribution, but is very useful in determining variations from month-to-month and indeed it is possible to infer to some extent the nature of the data distribution from the box plots. The box plot presented here is one of many calculated for the data and has been compiled using the *Minitab* data analysis software. The length of the whisker or tail, extending out from each box, is proportional to the amount of values that are either in the upper quartile range (25% of the values in the upper quartile) or in the lower quartile range (25% of the data in the lower quartile range). The end point of the lower and upper tail of the boxplot indicates the minimum value and maximum values (excluding outliers). The size of the box is defined by the number of values, which fall between the lower quartile and upper quartile, i.e. the middle 50% of the data (the inter-quartile range). The position of the box centreline is defined by the median value of the data set. Furthermore, any outliers which may be present in the monthly datasets are represented by a star on either extremity on the box plot. The outliers are not significant, but are included here to highlight the extremes in variability that can exist with wind.

Box plots bring a number of advantages in the early analysis of the data, from the obvious monthly variation in maximum, minimum and median wind speeds, to the less obvious distribution of wind speed data. In terms of the latter point, looking at an individual month, it is usually easy to see that the wind speed distribution is skewed and not normal (median is usually much closer to the lower set of values, both in terms of the box and the whiskers/tail). In fact it is possible to guess that the distribution skew is Rayleigh- or Weibull-like from the box plot. A less obvious benefit occurred when the box plot for November 2009 was examined and showed a surprisingly low mean and a small box. While three weeks of the month had been very calm, the first week had been very windy, so a problem was immediately highlighted, in this case an issue with logging data to a memory card.

The greatest number of outlier wind speed values were witnessed in May; this indicates that there was a large quantity of wind speed (indicated by the congested nature of the outliers) at unusually low and also unusually high levels, compared to the majority of the data for this month. Conversely there were no outliers present for the month of February, which is the month with the highest median, widest box plot and widest whiskers, indicating a bountiful month in terms of wind energy with quite a large, but consistent spread in wind speeds. The lowest average wind speed was witnessed in March, where the lower quartile is also the smallest, perhaps indicating that the proverb describing March as "coming in like a lion, but going out like a lamb" was much more the latter than the former in 2011 at this site. Similar box plots were also plotted for 2009 and 2010.

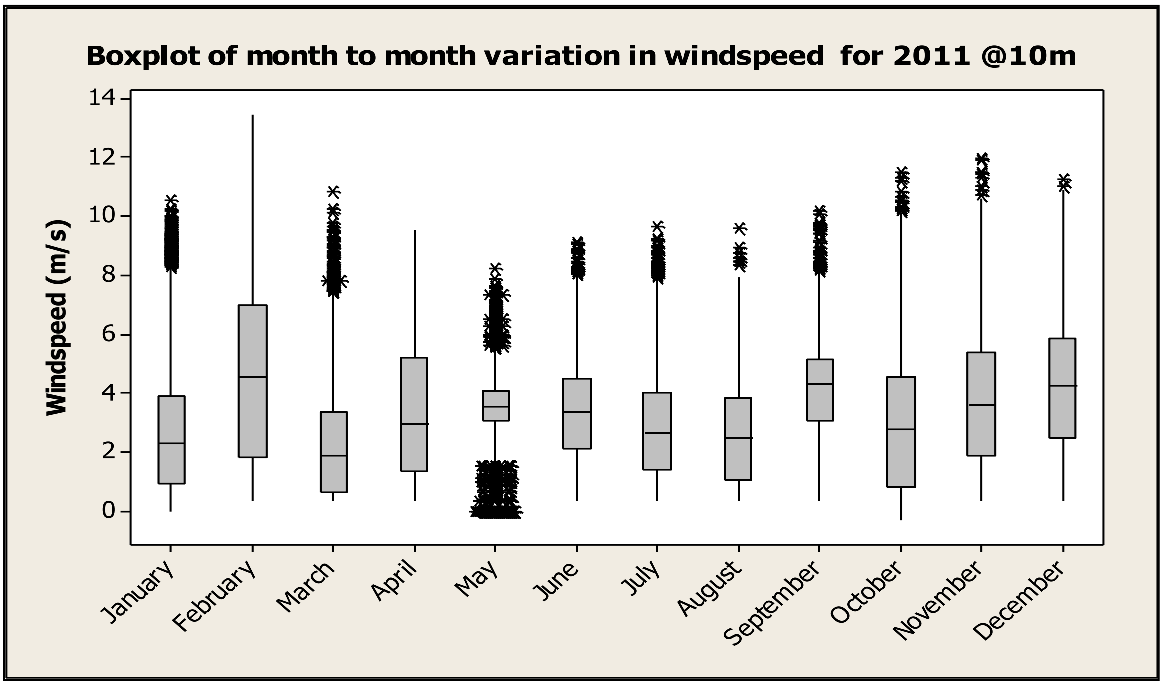


Figure 30 Boxplot of monthly variation in wind speed for 2011 at 10m measurement height.

Table 2 shows the *k* and *c* values for the 3-year data collection period at a measurement height of 10m. The *k* and *c* values for the site were calculated using the natural log method, mentioned in Chapter 3. Shown in Figure 31 is the application of the natural log method for the January 2011 data, which returned a *k* and *c* value of 1.26 (slope) and 2.69m/s respectively. This technique was used extensively in this work to calculate the *k* and *c* values for various heights and durations. For example in Table 2, it can be seen from the table of values that years 2009, 2010 and 2011 are very closely matched in terms of *k* and *c* values obtained. A consequence of the evenly matched *k* and *c* values is that a high degree of repeatability can be seen in the Weibull distributions for the site. This is a desirable characteristic for any potential site wind turbine installation project as it provides a clearer picture of the wind regime for the site.

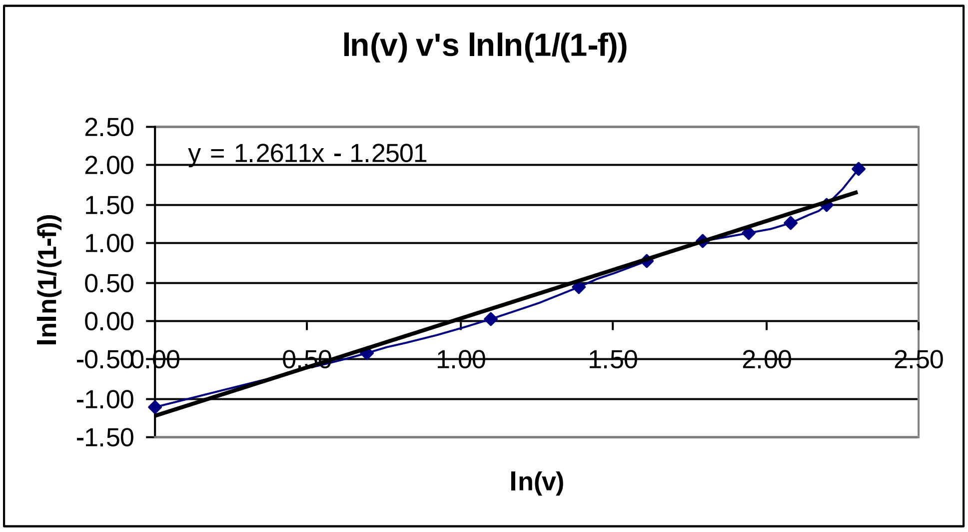


Figure 31 Natural log method for obtaining *k* and *c* values

Years	***2009***		***2010***		***2011***	
Parameters	**K**	**C**	**K**	**C**	**K**	**C**
January	1.60	4.30	1.50	3.52	1.26	2.69
February	1.43	3.40	2.19	2.98	1.36	4.41
March	1.70	3.88	1.40	3.29	1.30	2.86
April	1.64	4.37	1.70	3.40	1.37	3.40
May	2.60	1.64	2.20	4.30	2.71	3.97
June	1.70	4.60	1.70	2.80	1.86	3.42
July	1.60	2.10	2.00	3.50	1.62	3.11
August	1.50	2.21	1.70	3.40	1.61	2.73
September	1.70	2.63	2.03	4.01	2.58	4.68
October	1.84	3.11	1.70	2.71	1.40	3.25
November	1.88	3.13	1.40	3.71	1.55	3.85
December	1.32	2.71	1.70	3.05	1.75	4.65
Annual	1.71	3.17	1.77	3.39	1.70	3.59

Table 2 36-month average *k* and *c* values for the Bausch + Lomb manufacturing site

Figure 32 and Figure 33 show the histogram plots on *Minitab* for the *k* and *c* values for 2009, 2010 and 2011 respectively. The histogram plot in Figure 32 clearly indicates that the average *k* value for the site for the three year monitoring period is between 1.6 and 2.0

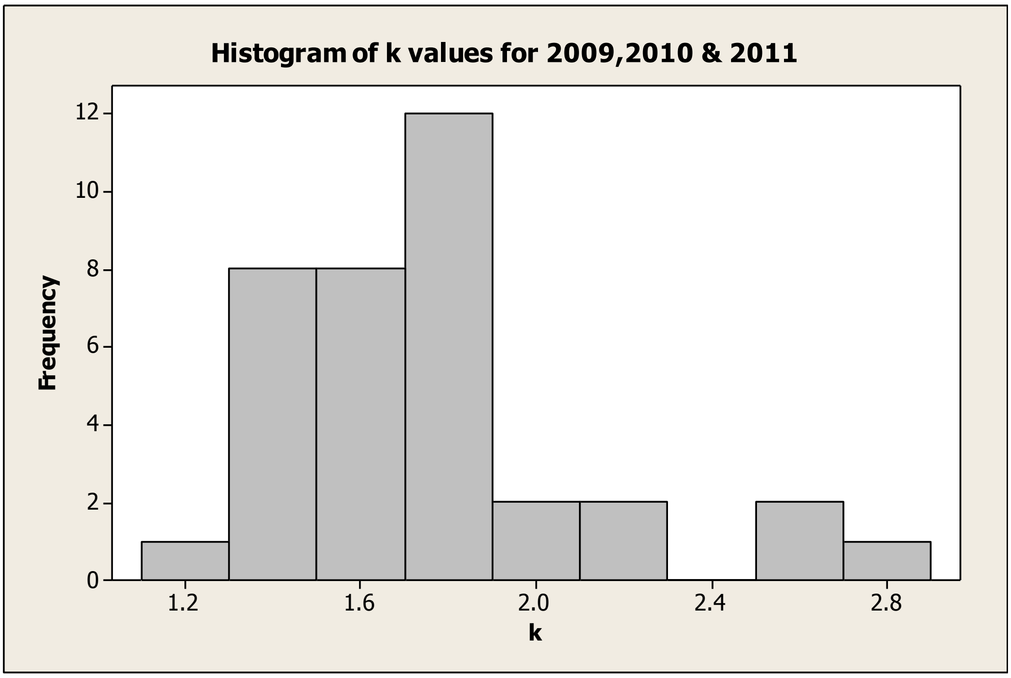


Figure 32 *Minitab* histogram of *k* values for 2009, 2010 and 2011

In Figure 33, the highest frequency *c* values lie between 2.8 and 3.6 for the 3-year monitoring period.

Figure 33 *Minitab* histogram of c values for 2009, 2010 and 2011

Figure 34 shows the *Minitab k* and *c* analysis using the 1-sample t-test for a 95% confidence interval. In the initial part of the analysis, the *k* values for 2009, 2010 and 2011 were analysed individually as were the *c* values. It can be seen that the mean annual k values from year to year fall within the 95% Confidence Interval for the one-sample 3 year stacked *k* and *c* values.

One-Sample T: k 2009, k 2010, k 2011, c 2009, c 2010, c 2011

Variable	N	Mean	StDev	SE Mean	95% CI
k 2009	12	1.7092	0.3222	0.0930	(1.5045, 1.9139)
k 2010	12	1.7683	0.2785	0.0804	(1.5914, 1.9453)
k 2011	12	1.698	0.479	0.138	(1.393, 2.002)
c 2009	12	3.173	0.965	0.278	(2.560, 3.786)
c 2010	12	3.389	0.472	0.136	(3.089, 3.689)
c 2011	12	3.585	0.719	0.208	(3.128, 4.042)

One-Sample T: 3 year k

Variable	N	Mean	StDev	SE Mean	95% CI
3 year k	36	1.7250	0.3608	0.0601	(1.6029, 1.8471)

One-Sample T: 3 year c

Variable	N	Mean	StDev	SE Mean	95% CI
3 year c	36	3.383	0.744	0.124	(3.131, 3.634)

Figure 34 *Minitab k*&*c* analysis using 1-sample t-test for 95% confidence interval

In addition to the Weibull shape parameter *k* results for 2011, the Energy Pattern Factor (*f*) or the ratio of the mean of the cube versus the cube of the mean of the wind speed velocities was calculated also. The ratio *f* was found to be 2.43, which, when referenced to the Energy Pattern factor graph in Figure 24 in chapter 3 corresponds to a value of approximately 1.70 which equates to the calculated value of 1.70 shown in Figure 34.

Shown in Figure 35 is the wind rose graph for January 2011. It outlines the direction in which the wind is blowing most frequently. In this case it's in the South Westerly direction, which indicates that a shadowing effect is present in the North Easterly direction, precisely the orientation in which the Bausch + Lomb manufacturing facility is situated with respect to the measurement mast. The presence of this shadowing effect will be looked at in more detail in section 4.3.

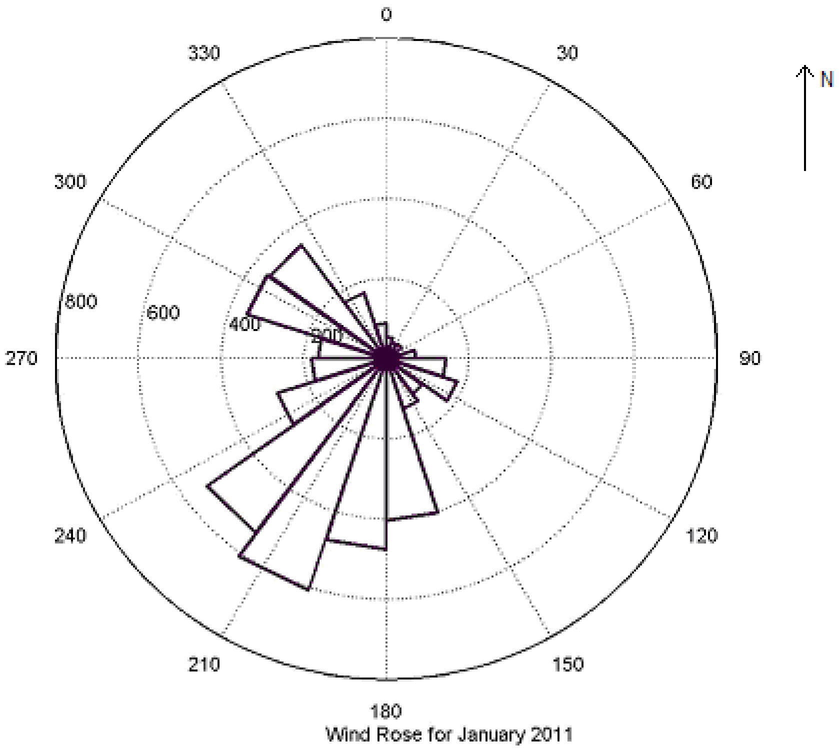


Figure 35 January 2011 Wind rose graph (0 degrees is due North), where diameters relate to frequency

The surface roughness factor, otherwise known as the Hellman exponent, was also calculated for the measurement site. The surface roughness factor is an important parameter in terms of site characterisation, as this is a factor which is inputted when carrying out wind speed scale up calculations for various heights, particularly scaling the wind speed values to the hub heights of commercial wind turbines. These approximate values were calculated specifically for the site in Figure 36 and compare favourably with the published reference data of 0.6 for 'stable air above human inhabited areas' (Kaltschmitt *et al* 2007). Figure 37 shows the published surface roughness factors for a variety of sites.

Year	*α*
2009	0.51
2010	0.60
2011	0.55

Figure 36 Hellman exponent values for the Bausch + Lomb site

Open sea, Fetch at least 5 km	0.0002
Mud flats, snow; no vegetation, no obstacles	0.005
Open flat terrain; grass, few isolated obstacles	0.03
Low crops; occasional large obstacles, $x/H > 20$	0.10
High crops; scattered obstacles, $15 < x/H < 20$	0.25
parkland, bushes; numerous obstacles, $x/H \approx 10$	0.5
Regular large obstacle coverage (suburb, forest)	1.0
City centre with high- and low-rise buildings	≥ 2

Figure 37 Published surface roughness factors for a variety of sites (Wikipedia 2013)

Figure 38 shows the wind speed scale up values for the Bausch + Lomb site for January 2011 using the $\frac{1}{7}$ power law equation. The pink line in the graph represents the scaled up values at 47m (hub height of Vestas V47 wind turbine), while the blue line represents the raw data obtained from the site at 10m.

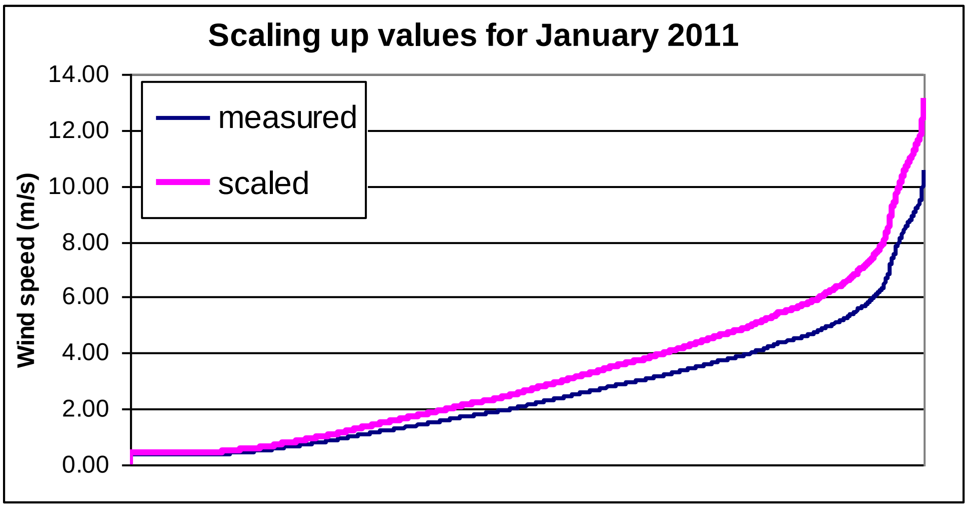


Figure 38 Wind speed scale up values for January 2011 using the $\frac{1}{7}$ power law equation

4.2 Site Weibull characteristics

A variety of factors contribute to making a site suitable for wind production. A prospective site must display a number of characteristics in order for consideration for a wind energy capacity installation. The site must generate suitable average wind speeds with closely matched standard deviations. As the Weibull distribution is often a very accurate match to the wind speed distribution at a measurement site, the values for *k* and *c* that arise from a Weibull analysis of a site must be suitable also. Figure 39 shows the 12 month Weibull distribution for 2009. A feature of this distribution is the 'spike' that is present for very low wind speeds of between approximately 0-1 m/s. These speeds are typically below the cut-in speed of all commercial turbines. Such a spike usually occurs as a result of a shadowing effect, the results of which, if ignored, can be detrimental to any wind site evaluation. This will be dealt with in more detail in the next section.

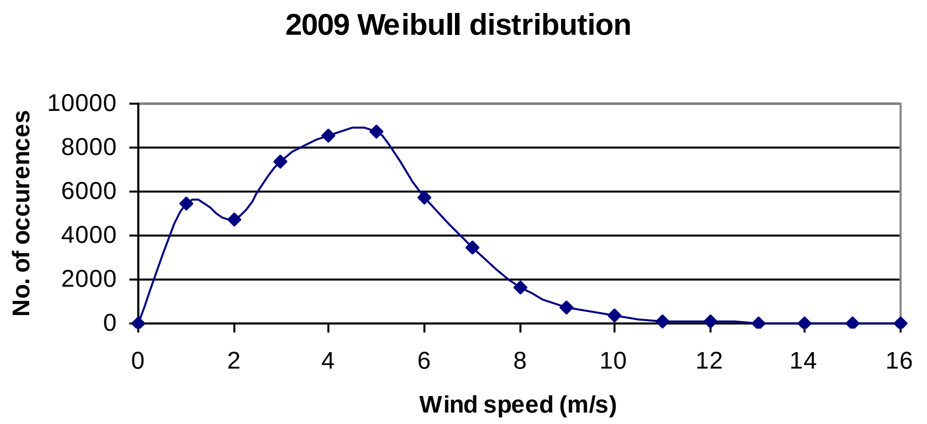


Figure 39 12-month Weibull distribution for 2009

4.3 Shadow effect analysis

Typically for very low wind speeds, such as 0-1 m/s, the frequency of such wind speeds is low. Frequencies should rise gradually for mid-range values, before dropping off dramatically for high wind speeds. This behaviour is mirrored in most monitored sites, especially when the monitoring mast is sufficiently tall. However, when the mast is lower, as may be expected for many early-stage autoproduction cases, where only a single turbine is expected to be installed and, so, cost may be a factor, there is a risk of wind shadowing. Usually this means some building or outcrop on the landscape impeding the wind from some quarters. This will have some impact on the measured distribution and also on the eventual power output, if the hub height is the same and the site is not moved.

This effect can be seen from the Weibull distribution obtained for the Bausch + Lomb monitored site in Figure 40. There is an initial spike in the data, whereby more than 3,000 data points were recorded at below 1m/s. Examination of the rest of the measured data (over 1m/s) shows the expected Weibull distribution shape.

Thus, a Weibull distribution for this data can be plotted and used as the basis for analysis, *if the spike is ignored*. As there were approximately 20,000 data points collected for the month, then the spike represents 3,000/20,000 = 15% of the data and consequently, any simple, Weibull-based analysis will be an assumption (as the distribution is clearly NOT a simple Weibull distribution) and will also lead to an overestimation of power, if this percentage of readings is ignored.

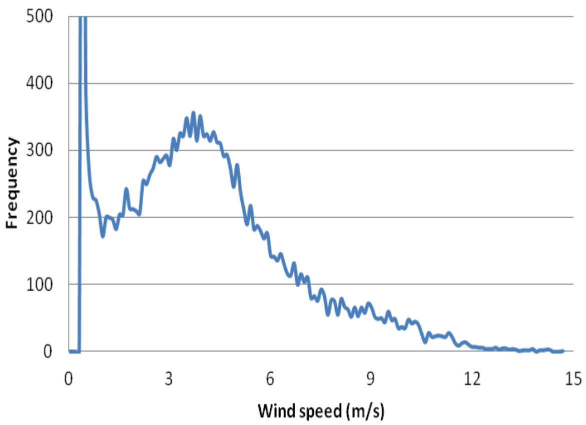


Figure 40 Shadowed data (<1m/s spike) from monitored site

4.4 Site comparisons

As a means of comparison, data sets from other sources were analysed and compared to the Bausch + Lomb data. Historical data sets from a 50m wind measurement mast, which was located at the Waterford Institute of Technology (W.I.T) campus and also from the Met Éireann M6 Buoy, located off the southwest coast of Ireland, were analysed. Figure 41 shows the location of the M6 buoy with respect to the west coast of Ireland.

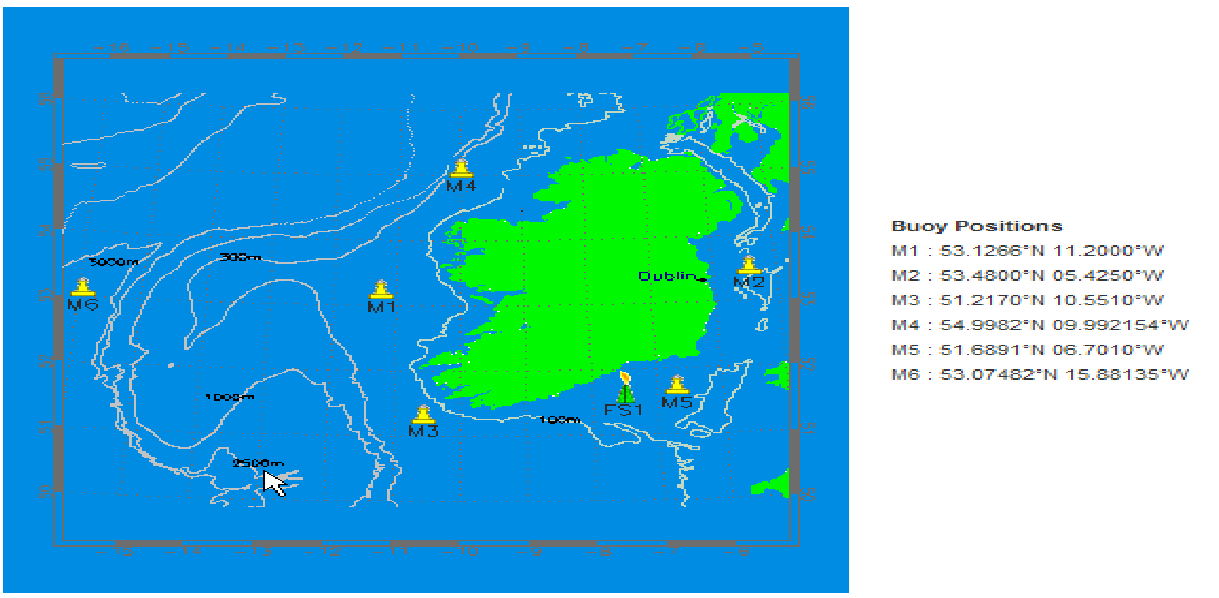


Figure 41 ***Irish Marine Weather Buoy Network*** **(*Marine Institute 2006)***

Figure 42, Figure 43and Figure 44 show the W.I.T *k* and *c* values, the M6 buoy *k* values and the M6 buoy *c* values respectively.

W.I.T Values *k* and *c* for 2006		
Month	***K***	***C***
September	1.70	4.30
October	2.16	3.88
November	1.21	3.45
December	1.82	5.31
January	2.37	6.03

Figure 42 W.I.T *k* and *c* values for 2006

M6 Buoy 3 year *k* values			
Month	***K (2007)***	***K (2008)***	***K (2009)***
January	1.91	2.18	2.55
February	1.91	1.78	2.75
March	1.60	2.06	3.27
April	1.35	3.03	2.72
May	1.53	2.46	3.00
June	1.98	2.43	2.05
July	2.04	2.41	2.71
August	1.74	2.95	2.13
September	2.15	2.03	2.44
October	2.50	2.99	2.37
November	2.12	2.34	2.61
December	1.73	2.56	2.16

Figure 43 M6 Buoy 3 year *k* values

M6 Buoy 3 year *c* values			
Month	***C (2007)***	***C (2008)***	***C (2009)***
January	10.88	10.91	11.10
February	8.82	8.94	6.09
March	7.96	9.89	10.12
April	3.44	8.65	8.16
May	5.73	6.10	8.16
June	5.74	7.54	6.09
July	6.04	6.89	7.33
August	6.62	7.83	7.52
September	7.12	7.35	7.92
October	7.78	10.43	7.58
November	7.89	8.84	11.13
December	12.80	9.52	10.60

Figure 44 M6 Buoy 3 year *c* values

The highest values of the Weibull shape parameter *k* were observed for the M6 buoy, owing largely to its offshore location on the west coast of Ireland. This location would be typically exposed to higher wind speeds out at sea in the Atlantic in comparison to the onshore inland locations. An interesting point to note, is that displayed in Figure 45, which is that, although the *k* values are higher month-to-month for the M6 bouy compared to the B+L data, a similar rising and falling pattern exists for both, whereby for example, as the *k* rises for the M6 buoy data it does also for the B+L data. This pattern is not as evident for the scale parameter *c*, however, as shown in Figure 46. A consequence of the M6 buoy having higher *k* and *c* values than both the W.I.T and Bausch + Lomb data sets, is the high average wind speeds as outlined in Figure 47. The W.I.T site possesses only marginally higher *k* values than the B+L site, however *c* values are an order of magnitude higher, due to the fact the data was analysed at a measurement height of 50m.

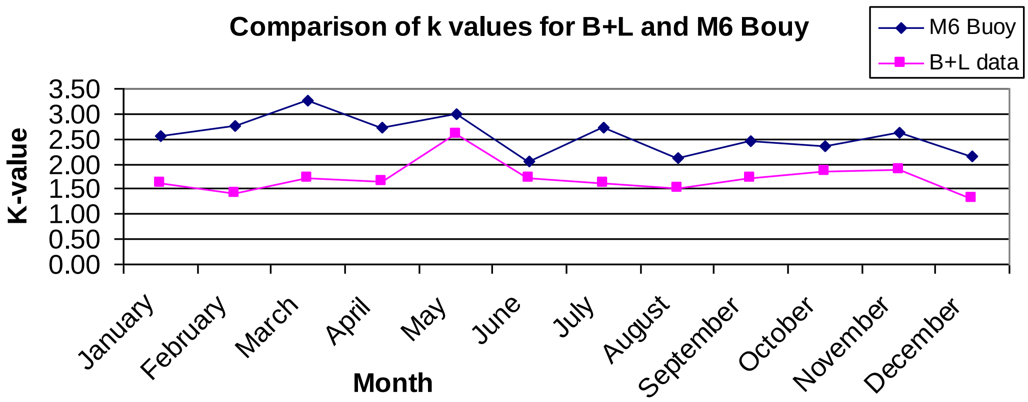


Figure 45 Comparison of *k* values for Bausch + Lomb and the M6 Buoy for 2009

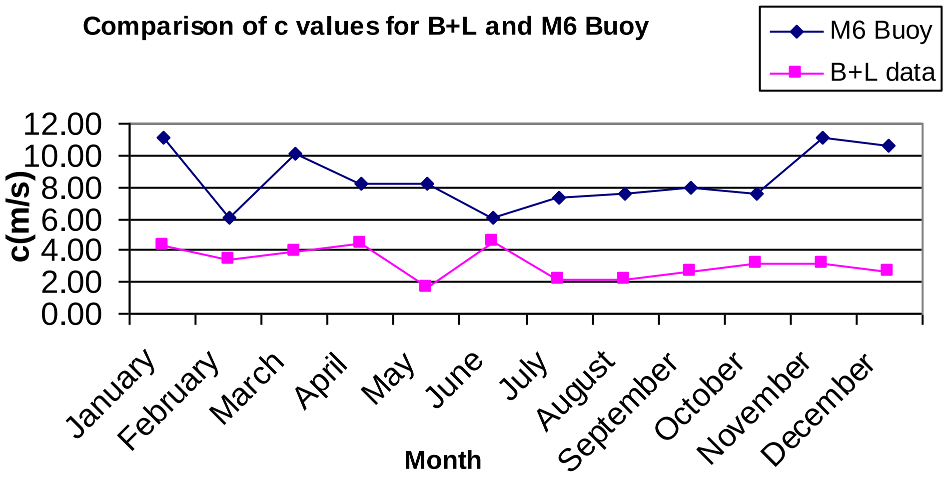


Figure 46 Comparison of *c* values for Bausch + Lomb and the M6 Buoy for 2009

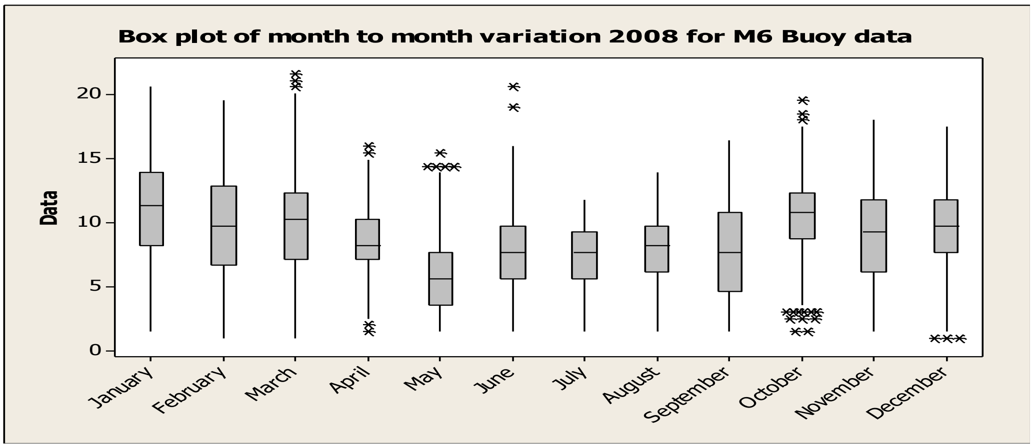


Figure 47 *Minitab* box plot of month-to-month variation in wind speeds for 2008 for the M6 buoy

4.5 Expected site energy and turbine output

One of the most important aspects of any site selection process is determining the energy output of the site, while consequently calculating the power output and matching a suitable wind turbine to the wind speed characteristics of the site.

This approach was applied to the 2010 Bausch + Lomb measurement data. The wind speed values were scaled up to a height of 50m. The average wind speed data was found to be 3.15m/s at 10m and when scaled up to 50m it was 4.22m/s. Thus when inputted to the energy equation, derived earlier, the energy output of the site was 6300 MJ, for the Vestas V47 swept area.

The power output for the site was then calculated by multiplying the energy output of the site by a C_p factor of 0.5 (which would be above the norm for most sites), returning a site power output of 726kW.

For the Bausch + Lomb site a number of commercial wind turbine power curves were analysed, in order to match a suitable wind turbine to the site. The Vestas V47 turbine (47m hub height) was found to have wind power output characteristics best suited to the site. The power curve for the Vestas V47 turbine is shown in Figure 48.

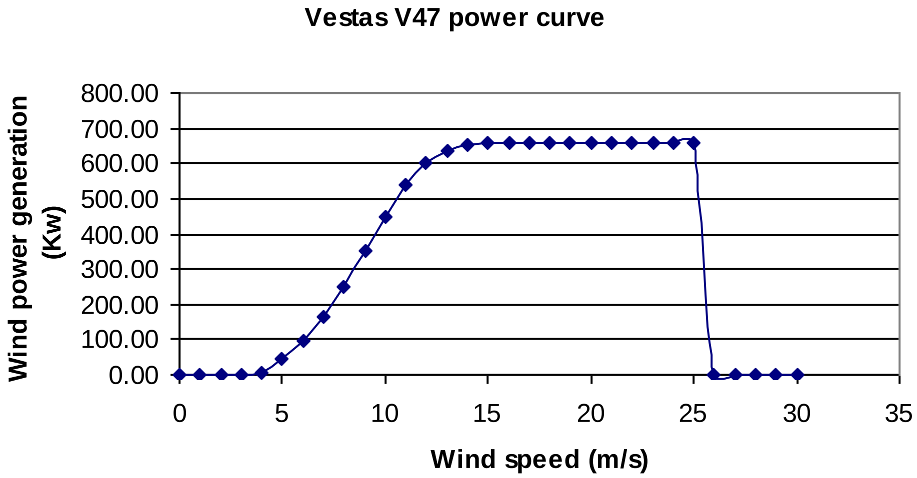


Figure 48 Vestas V47 power curve

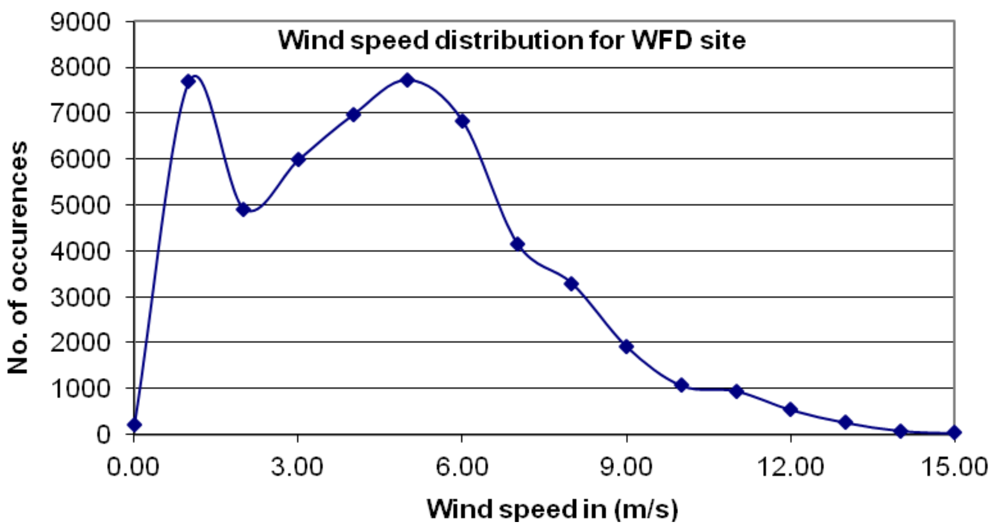


Figure 49 1/7th law scaled wind speed frequency distribution

Figure 49 presents the wind speed distribution for the Bausch + Lomb site power when scaling up the wind speed data collected from the site measurement mast, from 10m to 47m (hub height of the Vestas V47 turbine.) Figure 50 shows the estimated energy generated at 47m using the Vestas V47 wind turbine from Figure 48 at the Bausch + Lomb site.

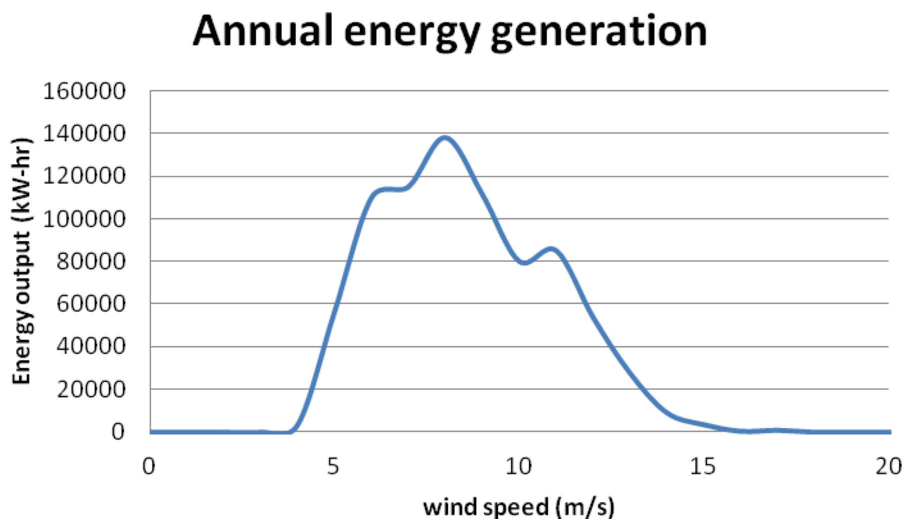


Figure 50 Energy generated at 47m using a Vestas V47 wind turbine at the Bausch + Lomb site

Additionally the power density as a function of height was calculated using Matlab, for different surface roughness factors, for the site at a measurement height of 10m as shown in Figure 51. Surface roughness factors ranging from 0.5 -2.0 are included in the graph. The largest surface roughness factor of 2 produces the greatest power density. A surface roughness factor of 0.56 was calculated for the Bausch + Lomb site as a three year average.

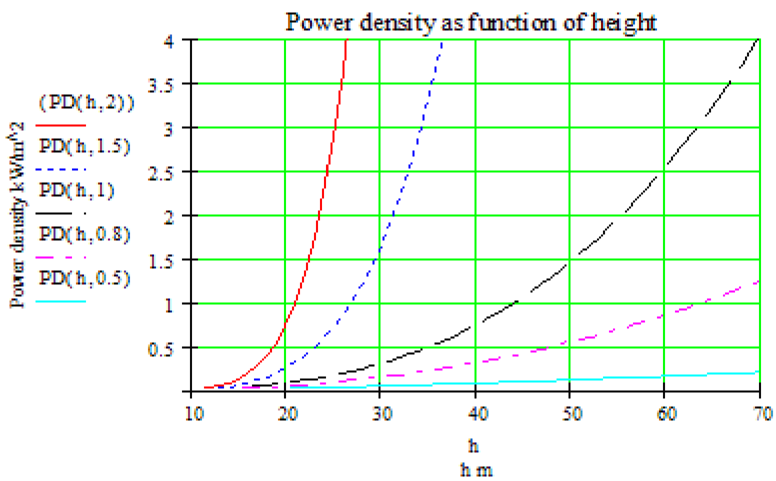


Figure 51 Power density as a function of height

4.6 Site wind predictions

The wind energy prediction method which is examined as part of this work is the persistence method of wind prediction, which specifically deals with short-term wind prediction. The persistence method of wind prediction is best described by the equation shown below:

$$P^{p}{}_{k}(H^{t}) = \{Y^{t-k+1}, Y^{t-k+2,\ldots} Y^{t}\}$$

Where,

$\{Y^{t}\}$ is a given time series

$Ht = \{Y^{0}, \quad Y^{1}, \ldots., Y^{t}\}$

P^{p} = Persistence process

k = forecast of the forthcoming values

(Solórzano *et al* 2010)

The persistence method of forecasting deals with very short term forecasting methods of the order of 10-30 minutes. The theory behind the persistence method of wind prediction relies on the basis of what has occurred in the very recent past will occur in the very near future. The persistence method has a number of varied applications; however, it can be strongly applied to wind energy applications. For the persistence model to hold true, the difference between the wind speed recorded in the recent past and the current wind speed must be close to zero. This application proved to be a suitable fit to the Bausch + Lomb suite of data as the recording interval for the raw data was 10 minutes, which agrees with the lower range of time intervals for the persistence method.

The graph shown in Figure 52 depicts some simple results underlining the validity of the Persistence model as applied to the Bausch + Lomb site data. In this graph, three distributions are shown of the difference between current and successive wind speeds, for the time intervals 10, 30 and 60 minutes. Hence the peak is centred for each curve at zero, indicating that for the majority of the wind speeds, even after the span of 60 minutes, there has been *no change* in wind speed. As may be expected, however, the peak is not quite as sharp after one hour, compared with a delay of only 10 minutes. Nonetheless, this is a simple means of showing that an accurate short term prediction can be simply to say that the wind will be the same as the current wind speed.

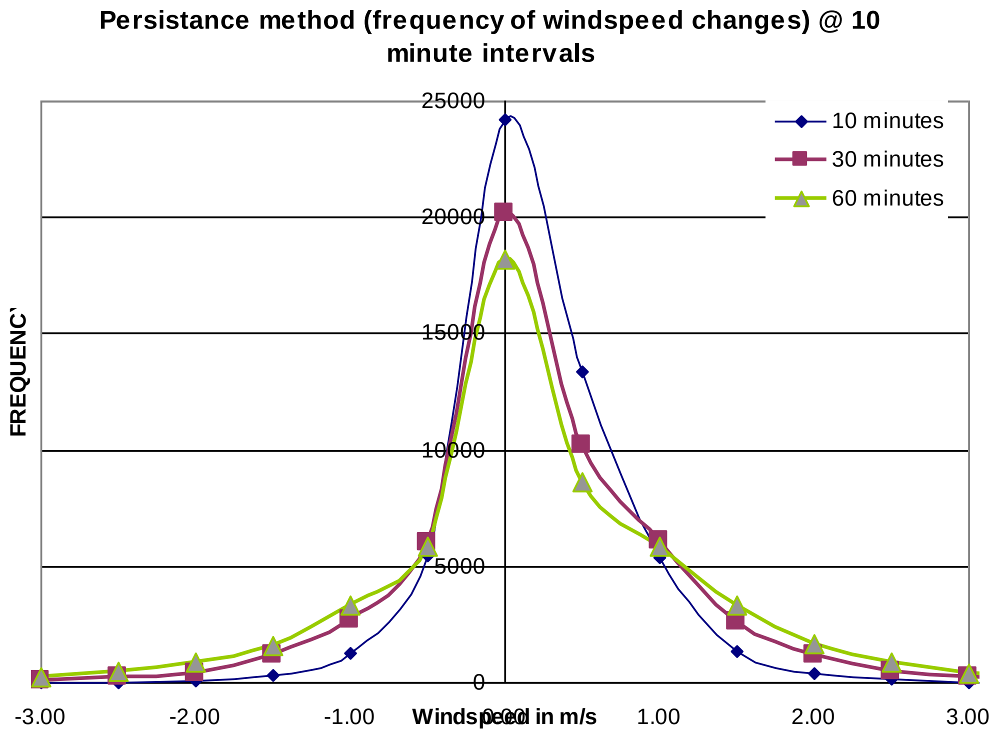


Figure 52 Persistence method at 10 minute intervals for the Bausch + Lomb site

5.0 Discussion and conclusion

A 10m wind monitoring mast was installed at the Bausch + Lomb manufacturing site. Wind speed and direction were measured at both 6m and 10m and the 3 year average wind speed was found to be 2.5 and 3.2 m/s respectively. The Weibull distribution was used to model the wind speeds as it closely matches wind speed distributions. The *k* and *c* values for the 3 year wind monitoring period were calculated and found to be 1.7 ± 0.1 and (3.4 ± 0.2) ms^{-1} respectively. In addition, a one sample t-test for a 95% confidence interval was carried out on *Minitab*, it was discovered that the mean annual *k* and *c* values from year to year fall within the 95% confidence interval for the one-sample 3-year stacked *k* values. This demonstrated a high degree of repeatability for the *k* values, which is a desirable characteristic for any potential wind energy development site in terms of predicting power output and revenue.

A shadowing effect was discovered in the North Easterly direction from the wind rose charts produced for the site, approximately in the same orientation as that of the Bausch + Lomb manufacturing facility with respect to the location of the wind measurement mast. The negative impact of disregarding the impact of shadowing was discussed and also led to a conference paper, a copy of which is included in the Appendices.

The surface roughness factor was calculated for each of the three-year wind monitoring periods producing an average value of 0.55, which is in close agreement with the published data of 0.6 for a site of this type.

The Energy Pattern Factor produced for the year 2011 for the measurement site produced a value of 2.43, corresponding to a *k* value of 1.70 for that year, which is in good correspondence with the value calculated from the Weibull distribution.

The wind speed values from the site were scaled up to a height of 47m (hub height of the Vestas V47 wind turbine) using both the $\frac{1}{7}$ power law and the scaling equation. Using the $\frac{1}{7}$ power law, the average 2010 wind speed was 4.2m/s, while using the scaling law returned a value of 8.5m/s. Ultimately, the $\frac{1}{7}$ power law approach was chosen, as this was a more conservative method and was a closer match to the published *Wind Atlas* estimates for this region. Taking into account average 2010 wind speed of 4.2 m/s (derived from the $\frac{1}{7}$ power law equation) the Bausch + Lomb site (at a scaled up measurement height of 47m) could be considered as a fair to moderate site in terms of observed wind speeds (Vanek *et al* 2012).

One of the key observations of this work arose during the site Weibull analysis phase, whereby a spike in the Weibull graph was observed for very low wind speeds in the order of 0-1 m/s. This manifested itself as a shadowing effect. The resultant Weibull spike should not be ignored as part of any wind site analysis as any simple Weibull based analysis that ignores the initial spike, will be an assumption (as the complete distribution is NOT a Weibull distribution) and also will lead to an overestimation of power, as this percentage of readings will be ignored.

The Bausch + Lomb site was compared with two other sites, namely the W.I.T. measurement site and the M6 weather buoy off the west coast of Ireland. As could have been expected, the M6 Buoy produced the highest average wind speeds at 12m/s and the highest Weibull shape parameters of *k* and *c* of 2.56 and 12.8m/s respectively.

A number of commercial wind turbines were examined as part of the turbine selection process for the site. The published power curves for these turbines were analysed and compared with the resultant site Weibull wind distribution. The key area of comparison was around the region of the manufacturers' stated cut-in speed and whether the majority of site wind speeds were outside of the turbine cut-in speeds. The Vestas V47 wind turbine was selected as the most suitable commercial wind turbine for the site as its power curve characteristics best suited the Weibull characteristics. The resultant energy and power output for the site were calculated for the 2010 data based on the specifications for the Vestas V47 turbine. The energy output is 6300MJ.

The persistence method of wind speed prediction was examined briefly in terms of the Bausch + Lomb data. At 10 minute intervals, this method proved to be a good fit for the data as the differences between consecutive wind speed values was predominantly zero. This is even true for one-hour intervals, albeit the spread in the differences for a 1-hour interval is larger than for the 10-minute interval.

5.1 Recommendation for further work

Based on the analysis that this work presents, a number of recommendations for further work can be made.

- The measurement height referenced in this work is at 10m, and scale up equations have been used to calculate the wind speeds at a height of 50m. It would be advantageous to install a higher wind measurement mast to enable a better understanding of the wind shear for the site and also the overall power generation possibilities for the site. This would allow better estimates for higher (than 50m) hub heights, as well as reducing significantly the shadowing effect.
- Explore in more detail the different methods of prediction to include ARMA (Autoregressive moving average) and ANN (Artificial neural networks). The ARMA model describes an individual time series and describes a forthcoming time series as a linear combination of historic values. ANN models employ a data driven approach to prediction, by nonlinear modelling of the observed data, independently of the input and output variables). This is a very flexible method of wind forecasting.

References

Aspe,S Wirz, R. (2011). *Small vertical-axis wind turbine concept.* Available: http://www.wirz.seas.ucla.edu/research.php?t=wd. Last accessed 3rd April 2013.

Assis, A. (2012). *Oil gains, gold edges lower in early trading.* Available: http://www.marketwatch.com/story/oil-gains-gold-edges-lower-in-early-trading-2012-04-17. Last accessed 23rd November 2012.

Barnard on wind (2013) Available: http*://barnardonwind.com/2013/02/23/why-arent-vertical-axis-wind-turbines-more-popular/* last accessed 5th April 2013.

Betz, A. (1966) *Introduction to the Theory of Flow Machines.* (D. G. Randall, Trans.) Oxford: Pergamon Press

Bianchi, F.D; Battista, H; Mantz, R.J; *Wind turbine control systems principles, modelling and gain scheduling design*. XIX 2070105.

Boccard, N (2008) *Capacity factor of wind power, realized values v's estimates.* Department of Economics University of Gerona.

Boyle,G (2007) *Renewable energy, power for a sustainable future* Oxford University press.

Boyle, G (2007) *Renewable electricity and the grid: the challenge of variability.* Earthscan, 2007.

Brazilian, Morgan, Denny E;O'Mally M (2004); *Challenges of increased wind energy penetration in Ireland.* Wind Engineering 28.1 (2004): 43-55

Britannica. (2012). *Numerical weather prediction.* Available: http://www.google.ie/search?q=%E2%80%98The+inability+to+spill+excess+generation+to+neighbouring+power+systems+will+make+balancing+power+on+the+island+%28north+and+south%29+difficult+with+such+high+win. Last accessed 10th Mar 2013.

Chang TP; *Performance comparison of six numerical methods in estimating Weibull parameters for wind energy application.* Applied Energy 88.1 (2011):272-282

Chefurka,P. (2008). *The looming energy shortfall can wind fill the gap.* Available: www.paulchefurka.ca/EnergyGap.html. Last accessed 1st Nov 2012.

Deloitte (2009) *Jobs and investment in Irish wind energy, powering Ireland's economy* (2009)

Department of Communications, Energy and Natural Resources (2011) Directive 2009/28 EC

Dowley,M (2010) *'A successful rooftop wind power project?*
Master of Science renewable energy thesis. Murdoch University, Western Australia

Ecotricity. (2013). *Wind parks gallery*. Available: http://www.ecotricity.co.uk/our-green-energy/our-green-electricity. Last accessed 5th May 2013.

Edwards S; Holroyd S; (2010) Strategic Environmental Assessment (SEA) of the offshore renewable energy development plan (OREDP) in the republic of Ireland.

EIA. (2012). Total energy. Available: www.eia.gov/totalenergy. Last accessed 5th May 2013.

EIA (2012) *Annual energy review 2011*. Available: http://www.eia.gov/total energy/data/annual/perspectives.cfm Last accessed 15th Feb 2013

Eirgrid (2013). *Grid 25.* Available: http://www.eirgrid.com/media/Grid%2025.pdf. Last accessed 5th May 2013.

European Renewable Energy Council (2011) *Mapping renewable energy pathways towards 2020 EU roadmap* (2011).

Foley,A.M;Leahy P.G; McKeogh E.J; *Wind energy integration and the Wales-Ireland interconnector.* Proceedings of the IEEE PES/IAS conference on sustainable alternative energy, Valencia, Spain. (2009)

Gregorie,M. (2002). *Aerodynamic references for small wind turbines.* Available: http://www.google.ie/imgres?imgurl=http://www.gregorie.ukfsn.org/freeflight/wind_turbine/pitch.jpg&imgrefurl=http://www.gregorie.ukfsn.org/freeflight/wind_turbine/&usg=__0cy7qCHuHUShHteTzNhuWMrM36c=&h. Last accessed 22nd November2012.

Grid 25 (2013) *A strategy for developing Ireland's electricity grid infrastructure for a sustainable and competitive future.*

Gupta R, and Biswas A (2009) '*Wind data analysis of Silchar (Assam India) by Rayleigh and Weibull methgods'* Vol 2 (1) pp010-024 Feb 2010

Harvey, C;Stenseth,K; Wohlmuth, M; *The Moyle HVDC Interconnector:project considerations,design and implementation.* AC-DC Power Transmission, 2001. Seventh International Conference on (Conf. Publ.No.485). IET, 2001

IWEA. (2012). *Wind Energy in Ireland.* Available: http://www.iwea.com/index.cfm/page/windenergyfaqs?#q19. Last accessed 5th June 2013.

IWEA (2013) *county map.* Available: http://www.iwea.com/index.cfm/page/windenergy onshore. Last accessed 14th March 2013

Kaltschmit M; Stricher W; Wiese A (2007) *Renewable energy – technology, economics and environment.* Springer 2007 W

Lang,S. (2008).Wind energy forecasting on the Irish power systems using a multi-scheme ensemble prediction system. Available: http://www.seai.ie/Publications/Renewables_Publications_/Energy_RD_D/Wind_Energy_Forecasting_on_the_Irish_Power_Systems-using_a_Multi-Scheme_Ensemble_Prediction_System.pdf. Last accessed 5th Feb 2013.

Marine work group Ireland. (2013). *Offshore wind farms.* Available: http://www.mwg.utvinternet.com/iss_or_owfs.html. Last accessed 6th Feb 2013.

McHugh. (2010). *Wind energy in Ireland.* Available: http://www.een-ireland.ie/eei/assets/documents/uploaded/general/Wind%20Energy%20Fact%20sheet.pdf. Last accessed 6th Sept 2012. Enterprise Europe Network. Waterford.

Metoffice (2012) Available: http://www.metoffice.gov.uk/media/image/n/m/virtual_met_mast_wind_frequency_graph.jpg

Portsmouth Sustainable Energy & Climate Change Centre - PSECC . (1996). *The Potential of Offshore Wind.* Available: http://www.psecc.org.uk/html/wind_.html. Last accessed 15th Jan 2013.

Porte-Agel,F:Yu-Ting,W;Hao,L;Conzemius,RJ (2011) *Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms*. Journal of wind Engineering and Industrial Aerodynamics Volume 99, Issue 4, April 2011, Pages 154-168

RTE (2012) Available: http://www.rte.ie/news/business/2012/040/315804-oil-higher-in-asia-on-chinese-demand-hopes/ Last accessed 9th April

Sanchez, I; (2006) *Short term prediction of wind energy production.* International journal of forecasting 22.1 (2006): 43-56

SEAI (2012) *Wind Energy* Available: http://www.seai.ie/renewables/wind_energy/ Last accessed 27th March

SEAI (2012) *Wind atlas* Available: http://www.seai.ie/renewables/wind_energy/wind/maps Last accessed 27th March

SEAI. (2013). *Wind farms in Ireland.* Available: http://www.seai.ie/Renewables/Wind_Energy/Wind_Farms/Wind_Farms_in_Ireland/. Last accessed 5th Feb 2013.

SEAI. (2013). *Wind energy roamap to 2050.* Available: http://www.seai.ie/Publications/Energy_Modelling_Group_/SEAI_2050_Energy_Roadmaps/Wind_Energy_Roadmap.pdf. Last accessed 1st May 2013.

Sanusi Y.K; Abisoye S.G (2011) *Estimation of Wind Energy Potential in Southwestern Nigeria.* Physical Science Department, Yaba College of Technology, Nigeria. Department of Pure and Applied Physics, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. The Pacific Journal of Science and Technology. Volume 12. Number 2. November 2011 (Fall).

Solorzano YC; Gutierrez-Trashorras; AJ;Xiberta-Bernat J (2010) '*Analytical methods for wind persistence: Their application in assessing the best site for a wind farm in the State of Veracruz,* Mexico'Renewable Energy 35 (2010) 2844e2852

Twomey,J. (2006). *Wind farms.* Available: http://www.teagasc.ie/ruraldev/docs/factsheets/49_WINDFARM.pdf. Last accessed 10th Feb 2013.

Vanek F, Albright L, Angenant L (2012) 'Energy systems Engineering Evaluation and Implementation McGraw Hill

Van Der Vleuten E; Raven R; *Lock in and change: Distributed generation in Denmark in a long-term perspective.* Energy policy 34.18 (2006): 3739-3748

Wind energy the fatcs. (2012). *Onshore windmaps.* Available: http://www.wind-energy-the-facts.org/en/appendix/appendix-a.html. Last accessed 10th May 2013.

Wind energy direct (2013) *Munster joinery case study* (2013)

Wikipedia. (2013). *Betz' law.* Available: http://en.wikipedia.org/wiki/Betz'_law#Proof. Last accessed 7th May 2013.

Windbyte. (2012). *The wind problem in a nutshell.* Available: http://www.windbyte.co.uk/wind. Last accessed 10th Jan 2013.

Windbyte. (2012). *Distributed generation and smoothing.* Available: http://www.windbyte.co.uk/wind. Last accessed 10th Jan 2013.

Wind power engineering (2013) *A shorter executive summary for DOE's2011 Wind technologies market report.* Available: http://www.windpowerengineering.com/construction/projects/a-shorter-executive-summary-for-does-2011-wind-technologies-market-report/. Last accessed 12th Jan 2013

Waewsak J, Chancham C, Landry M and Gagnon Y; "An Analysis of Wind Speed Distribution at Thasala, Nakhon Si Thammarat, Thailand", Journal of Sustainable Energy & Environment 2, p51-55, 2011

Wind Power Program (2011) 14. *Wind turbine power output variation with steady wind speed.* Available: http://www.wind-power-program.com/turbine-characteristics.htm. Last accessed 6th May 2013

Wind Energy Direct (2009) *Munster Joinery case study*. Available: http://www.windenergydirect.ie/wp-content/uploads/2010/09/windenergydirect-munster-joinery-case-study-2009.pdf Last accessed 6th May 2013

White. S (2012) *Meeting Irelands renewable energy targets.* 16th April 2012

Winddea (2012) Available: http://www.windea.org/technology/ch02/imgs/2_2_2 img1 1.jpg. Last accessed 15thFebruary 2013

Appendices

Appendix I – Conference Publication

This was published at the 1st global virtual conference 2013 (GV-conf 2013) in conjunction with Golce Delchev University Macedonia & THOMSON ltd. Slovakia, April (8-12) 2013.

Shadowing and averaging errors in wind autoproduction analysis

John Flynn
Eamon Molloy, Paul O'Leary
Waterford Institute of Technology
Contact email: John.flynn@bausch.com

***Abstract*—** This paper describes power estimation errors that can occur in the development of sites, particularly small-scale developments. Measurements recorded locally over a four year period are used to underline this concept. Both the desk-based wind atlas estimation and also the wind shadowing effect can lead to an over-estimation of the power potential of a given site. Small-scale developments such as autoproduction or smart grid distributed energy generation could be impacted by these easily remedied errors.

Keywords; wind power estimation; autoproduction, distributed generation

Introduction

Wind energy converters are increasing the contribution to renewable energy generation, not alone in wind farms, but also in electricity auto-production. Electricity autoproduction will form a key component in the distributed generation of future smart grids and is even now an attractive option for users with large energy demands, primarily to reduce their energy costs, with a (usually) small generation surplus to on-site demand being exported to the grid. Two common techniques for viability assessment of a proposed wind energy converter autoproduction project are examined in this work, in terms of their reliability and common errors that can arise in interpreting their results.

One technique involves the desk-based analysis of the long-term average wind speed. Long-term average wind speed data is mapped for most countries and permit estimates for the locality of the proposed project, for example in [1]. The advantage of such an approach must be tempered by absence of site-specific data, such as terrain and in particular the wind frequency distribution.

A second, more elaborate and more expensive technique entails erecting a wind monitoring mast. Depending on the size of the proposed auto-production unit, this expense may preclude the erection. Also related to the proposed unit size is the actual monitoring height. In Ireland for example, certain planning permission waivers exist for hub heights of less than 10m (domestic) or 20m (commercial, agricultural, industrial) leading to the erection of monitoring masts of 6-10m height. At such heights the risk of wind shadowing, causing unusually large low or zero wind speed readings, is also a risk. These readings are typically below the cut-in speed of any turbine and appear to represent little or no energy, but discarding them for these or other reasons leads to an over-estimation of the likely annual electrical energy output.

Finally, the analysis of wind data and the prediction of annual output often includes the matching of the wind speed frequency distribution to a Weibull distribution. The impact of the potential errors caused by the shadowing effect will be explained in the context of a mapping to the Weibull distribution. The source data is derived from readings taken at 6 and 10m over a period of four years.

Measurement Technique

A variety of parameters contribute to making a site suitable for wind production. A prospective site must display a number of characteristics in order for consideration for a wind energy capacity installation. The site must generate suitable average wind speeds with closely matched standard deviations.

Wind Monitoring

A wind measurement mast has been erected at the Bausch & Lomb Waterford manufacturing facility and has been collecting significant volumes of data. The monitoring is performed by a Nexgen model, with wind speed measured using an NRG # 40C model anemometer and direction being measured using an NRG #200P model. Measurements are taken at 6m and 10m and recorded on a Nomad 2 datalogger. The sensors record the wind speed and direction at 6m and 10m respectively, averaged over 10 minute intervals. To date in 48 months worth of data has been collected, in excess of 200,000 data points.

Data Analysis

Data is periodically, manually retrieved by swapping digital memory cards for further software analysis using Excel, Minitab and the *R* programming language for statistical computing and graphics.

Results

The Weibull distribution is usually the expected closest distribution to any long-term frequency distribution of measured wind speed and is consequently the basis for much of the analysis and crucially the predicted available power. The Weibull distribution has two main parameters the Shape parameter, *K*, and the scale parameter, *C*. The purpose of the Weibull distribution when applied to wind speed data is to provide a model/regression for that particular data set, so one can decipher the frequency of a particular wind speed.

Shape parameter k

The shape parameter, k, and the scale parameter, *C*, characterise the Weibull distribution. The units of the *k* parameter are always dimensionless, while the units of the c parameter are in m/s. A larger value for *C*, indicates a larger value for the base, and a higher *k* value, meanwhile a lower *C* value, also indicates a lower *k* value.

For *k* values up to 2, the Weibull distribution is an accurate means of modelling the Weibull distribution, for a *K* value greater than 2, the Rayleigh distribution is used.

Scale parameter, C

The scale parameter/parameter describes the scale of the Weibull distribution and its units are in m/s.

This work was funded in part by Bausch and Lomb through their postgraduate sponsorship programme.

Cube of mean versus mean of cube (wind speed)

Quite often wind speed for a given site is expressed in terms of the long term average. A mistake sometimes made is to use this figure to estimate the site's potential wind power.

The essence of the mistake is to ignore the difference between the cube of the mean and the mean of the cube of any parameter. This is however, not a fixed error and will vary with the distribution of the parameter in question.

This is particularly important, especially when applied to wind energy measurements and assessments and the size of this difference depends on the shape parameter, *k*. Given that the wind power potential may be expressed as:

$$P = \tfrac{1}{2}\rho A v^3 \qquad (1)$$

where *A* is the swept area of a proposed turbine, *ρ* is air density and *v* is the wind velocity.

As there is a cubic relationship between the power available in the wind and the velocity, this makes the power calculation very sensitive to velocity estimates, i.e. the difference between cubing the long-term mean velocity and the mean of the cube of the same velocity is far more pronounced.

If the wind distribution may be assumed to have a Weibull distribution, then, by starting for example from the analysis in [2], the ratio of the two calculations can be shown to be:

$$f = \frac{\langle v^3 \rangle}{\langle v \rangle^3} = \frac{\Gamma\left(1+\frac{3}{k}\right)}{\Gamma^3\left(1+\frac{3}{k}\right)} \qquad (2)$$

where Γ is the Gamma function.

Given that the long-term measured wind speed frequency distribution can often be accurately modelled by a Weibull distribution, the relationship in equation (2) clearly highlights the need at a simple level to not cube the long-term mean to approximate future wind power, but more importantly also highlights how the *shape* of the frequency distribution plot influences the magnitude of the error.

Figure 1 shows a simulated plot of the relationship between the shape factor and the ratio in equation (2).

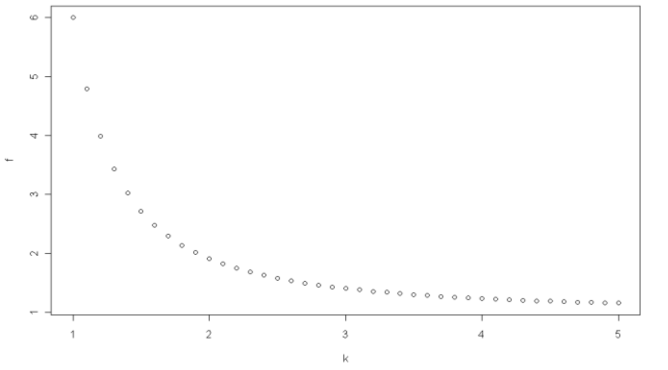


Figure 1 Ratio of mean cubed to cubed mean wind speed, as a function of *k*

Note for example the case of *k=2* (Rayleigh distribution) and the value used by most wind energy converter manufacturers to estimate annual energy production (for example [3]), the ratio is almost 2, meaning that using the cube of the mean long term wind speed underestimates the power by a factor of 2. Many urban landscapes will have *k* values of between 1 and 2. For the site monitored here, the average value for *k* was 1.7, whereas the calculated average value for the same period for a 3 metre weather buoy in the Atlantic Ocean was *k*=2.

Wind Shadowing

Typically for very low wind speeds, such as 0-1 m/s, the frequency of such wind speeds is low. Frequencies should rise gradually for mid-range values, before dropping off dramatically for high wind speeds. This behaviour is mirrored in most monitored sites, especially when the monitoring mast is sufficiently tall. However, when the mast is lower, as may be expected for many autoproduction cases, there is a risk of wind shadowing. Usually this means some building or outcrop on the landscape impeding the wind from some quarters. This will have some impact on the measured distribution and also on the eventual power output, if the hub height is the same and the site is not moved.

This effect can be seen from the Weibull distribution obtained for our monitored site in Figure 2, is the initial spike in the data whereby more than 3000 data points were recorded at below 1m/s. Examination of the rest of the measured data (over 1m/s) shows the expected Weibull distribution shape.

Thus a Weibull distribution for this data can be plotted and used as the basis for analysis, *if the spike is ignored*. As there were approximately 20000 data points collected for the month, then the spike represents 3000/20000 = 15% of the data and consequently, any Weibull based analysis will be an assumption (as the graph is NOT a Weibull distribution) and also an overestimation, if this percentage of readings is ignored.

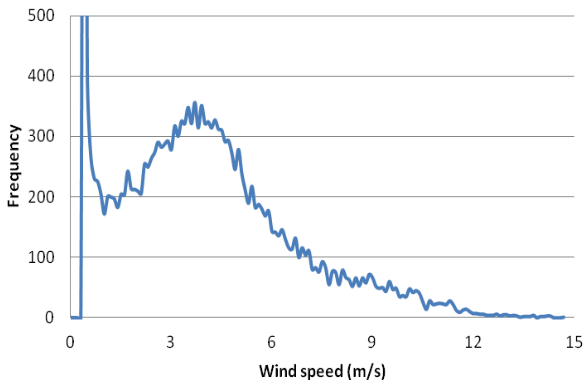


Figure 2 Shadowed data (<1m/s spike) from monitored site

Discussion

This work presents two potential pitfalls in estimating the potential power available from wind energy conversion, especially in the case of smaller scale developments, such as those in autoproduction or distributed generation of electrical energy.

In either case, the consequence of the error can be absorbed and even remedied, if some basic knowledge of the wind speed frequency distribution is available, in the case of the mean speed, or analysed correctly, in the case of wind shadowing.

Acknowledgments

The authors would like to acknowledge the support of Bausch & Lomb (Waterford) for one author (John Flynn).

References

[1] ESBI Consultants, Project Report Republic of Ireland – Wind Atlas 2003, Sustainable Energy Authority of Ireland http://www.seai.ie/Renewables/Wind_Energy/Wind_Maps/

[2] J.V. Seguro, T.W. Lambert, Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis, Chelsea Green Publishing, 2004, Page 37.

[3] Paul Gipe, Wind Power, Renewable energy for home, farm and business, d ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

.

Appendix II –Site Box plots