Department of Mechanical and Aerospace Engineering

An Assessment of the Accuracy and Potential of

LIDAR in the Wind Industry

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science in Renewable Energy Systems and the Environment

2014

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<u>Acknowledgements</u>

I would like to extend my thanks to my family and friends for their support and advice throughout the course of this thesis.

I would like to acknowledge my employers support which allowed me to complete this thesis in a part time capacity. Without the ability to do this it would never have been possible.

Finally and most importantly I would like to thank my supervisor, Dr. Andrew Grant, for his continued support throughout my MSc journey and in particular with this thesis.

<u>Abstract</u>

Accuracy in wind resource assessment is becoming increasingly important with the growing need for the wind industry to reduce the cost of energy. Remote wind measurement devices such as LIDAR are well known and are used to help wind resource predictions. However, the use of LIDAR as a single source of measurement is not fully accepted.

This thesis explores the use of LIDAR and the accuracy of the device's measurement relative to the industry accepted meteorological (Met) Mast. A LIDAR is to be installed at an onshore location and the accuracy of its measurement campaign is to be compared to that of a Met Mast. The process for installing the LIDAR is documented and the analysis discussed. A Power Performance Test (PPT) is conducted using a Met Mast to assess other areas where LIDAR can add value. The value of the PPT is proven and the benefit which can be realised through the use of a LIDAR is determined. The current and future of resource assessment is discussed, and the potential for LIDAR devices to provide innovative solutions within the industry is evaluated.

This thesis shows that a Met Mast is an accurate form of wind measurement and that PPTs have value as it is not unusual for a wind turbine to be significantly underperforming. LIDAR measurement accuracy will continue to improve and are likely to have significant impact on the wind industry in the coming years.

Table of Contents

Table of Figures

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1. Introduction

The majority of the energy we use in the UK is generated from burning fossil fuels such as natural gas and coal. It is widely accepted that the increased CO_2 levels in our atmosphere are a direct result of burning these fossil fuels and this is causing global warming and the increased frequency of extreme weather events.

The reduced availability of these finite fossil fuels means more remote and costly exploration is necessary and as a result the cost of these resources is increasing. Here in the UK there is a desire for a more secure energy supply as currently these resources are largely imported and open to price fluctuations. Government targets are driving a move away from fossil fuels in the search for a reduction in green house gas emissions and a more secure supply of energy. As a result, more sustainable methods of energy generation are being utilised.

One of the more developed sustainable energy sources is wind. Over the past decade, wind energy has become the fastest growing energy source in the world [1]. Energy generation from wind is at the forefront of the UK's national energy policy and in recent times, onshore wind was the only renewable energy source that could compete with more conventional generating methods such as gas or nuclear.

In terms of technology onshore wind is approaching maturity [2]. As one of the more mature renewable sources of energy, onshore wind currently plays a leading role in the generation of renewable electricity in the UK with over 4800 MW installed capacity in 2012 [3].

New incentives published at the end of 2013 reflect the maturity of the onshore wind industry. Onshore wind farms are now receiving lower subsidies so the reality is that more marginal wind farms will not be brought forward [4]. The reason for this is that it is claimed that onshore wind developers no longer need as much state support because of the considerable investment in this industry in recent times [5].

In contrast, offshore wind saw an increase in the recently published incentives to encourage long-term investment. The capital costs associated with the construction of an offshore wind farm are significantly more than an equivalent onshore wind farm and the industry itself is far less mature. However, there is greater potential with the resource offshore. The UK government claim there will be a deployment of up to 16 GW of offshore wind by 2020 and 39 GW by 2030 [6]. However, it is vital that costs are driven down to make the offshore wind projects associated with these claims cost more effective.

Resource assessment which is aimed at predicting the future energy production is crucial to the successful development of wind farms. To accurately predict future energy production, wind measurement tools such as Met Masts are used. As the wind industry has grown, the demand for more accurate measurement techniques has increased leading to new technologies being developed such as Laser Detection and Ranging (LIDAR) devices which use a laser to measure wind speed. LIDAR systems offer a cost effective alternative to Met Masts, in particular for offshore wind, as they do not require the capital intensive foundations or structures on which to place the measuring equipment.

With the growing need for wind energy to become more cost effective, it is vital that technologies like LIDAR are explored. The purpose of this thesis is to assess the accuracy of a LIDAR device compared to the industry accepted Met Mast and to determine if LIDAR can help drive down the cost of offshore wind.

2. Objectives

This section outlines the overall objectives which this thesis intendeds to achieve. The scope of the thesis goes far beyond the initial work required to assess the accuracy of a LIDAR and as a result primary and secondary objectives have been identified. The reason for this is that they involved two separate work streams but overall have been combined for this thesis. The scope for each objective is discussed in this section.

2.1. Primary Objective

The Primary Objective is to assess the accuracy of a LIDAR when compared to a Met Mast for the purpose of wind measurement. This assessment involved the installation and commissioning of a LIDAR at an onshore wind farm in the locality of a Met Mast. A measurement campaign was then conducted using both measurement systems and the results were compared.

Following a successful assessment, it was intended that a similar comparison could be conducted offshore to provide evidence that the same accuracy could be achieved in offshore conditions.

2.2.   <u>Secondary Objective</u>

The Secondary Objective of this thesis was to investigate areas where LIDAR could be used to reduce the overall cost of a wind farm. The area which this thesis concentrated on was the PPT which current European standards state can only be performed by a Met Mast.

Firstly an informal PPT on a wind turbine was conducted according to the guidelines set out in the European standards. The results of the test were then analysed to determine the benefit of the test at a wind farm. If the PPT provided benefit it was intended that a formal test would be conducted, and in parallel a test using a LIDAR to show that the use of a Met Mast should no longer be a requirement.

This additional work was time constrained so if it was not possible to complete it, an analysis based on the Secondary Objective would be conducted. This would give insight into areas where improvements could be seen and provide the basis for further study in this topic area.

An investigation into the current state of the wind industry was conducted including the status of remote monitoring systems such as LIDAR and their expected market growth in this fast moving industry.

3. Literary Survey

To properly assess how new wind measurement tools such as LIDAR could impact on the wind industry, resource assessment and its importance with regard to developing wind farms needs to be understood. This section introduces wind energy and the impact which accurate resource assessment can have.

Wind is the result of the sun heating the Earth's surface. When the Earth's surface is heated up, the pressure drops in the air above it and it rises into the atmosphere. The opposite happens when the Earth's surface is cooled; areas of low pressure are created. Air will move toward an area of low pressure and away from an area of high pressure. This response of air to pressure differences is wind. This is displayed in the Figure 1.
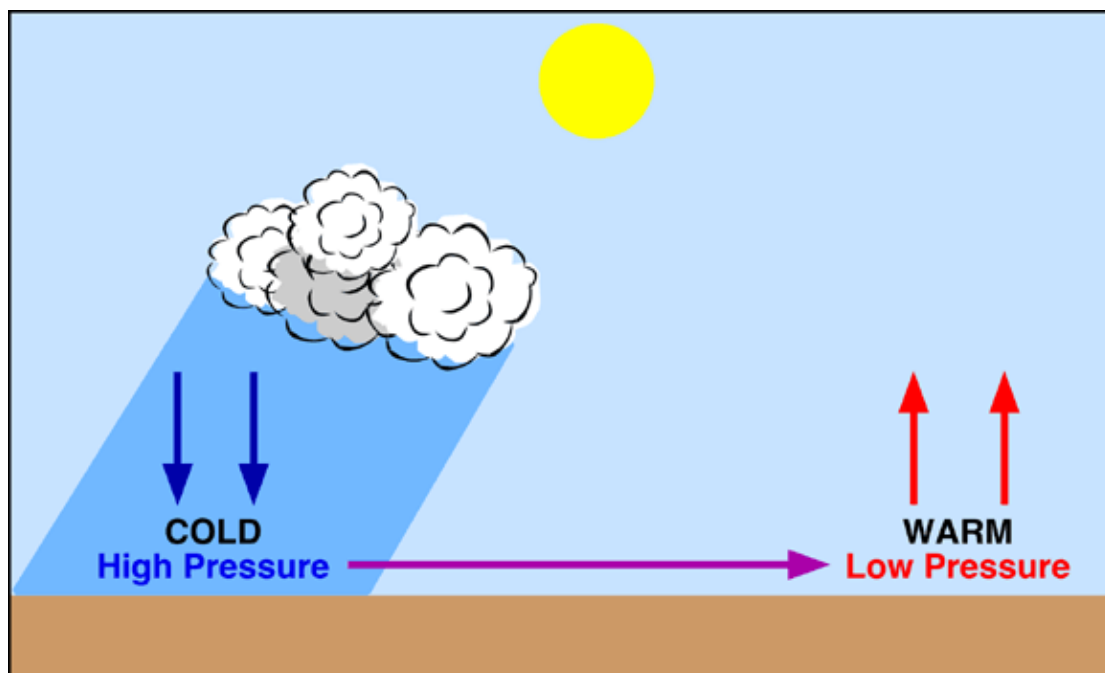
Figure 1: How wind is created [7]

3.1. Wind Turbines

Wind turbines, like that displayed in Figure 2 are used to harness the energy in wind.

Figure 2: Wind Turbine Example

Wind turbines usually have two or three blades which are rotated by the wind. The blades are connected to a rotor and this rotates the main shaft and the generator to produce electricity.

To take advantage of the greater wind speed, wind turbines are installed on towers above the ground. The electricity generated can be used to power houses or if they are large (~ >1 MW), wind turbines can be connected to the electricity grid to distribute the electricity on a bigger scale to where it is needed across the country.

A wind turbine must operate efficiently and reliably in a wide range of wind conditions. A number of components including the yaw motors, pitch system and nacelle anemometer allow the wind turbine to adjust and adapt to the different conditions it experiences.

A key characteristic of a wind turbine is its power curve. The power curve for a wind turbine describes the expected amount of power output that can be generated as a function of wind speed. The power curve is a line on a graph which describes the amount of energy the wind turbine will produce at different wind speeds at a hypothetical ideal site. Wind turbine suppliers will use power curves as a guarantee of their wind turbines' performance and warrant the associated power curve as part of a contract for a wind farm. An example of a power curve is given in Figure 3.

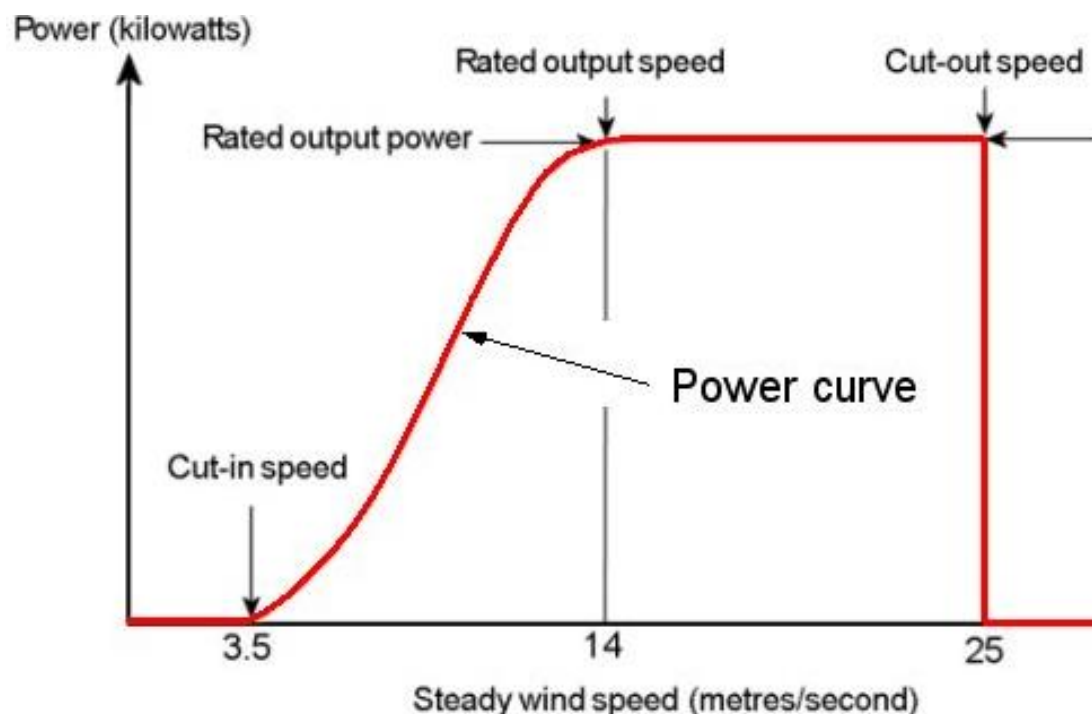*Figure 3: Wind Turbine Power Curve Example [8]*

In Figure 3 it can be seen that the wind turbine produces zero kilowatts until it reaches 3.5 meters per second (m/s). The wind turbine then starts to produce energy, and this energy increases rapidly as wind speed increases up to its rated output speed when it flattens out. The wind turbine then produces power at its rated output until it reaches an unsafe wind speed for the wind turbine design and cuts-out, which in Figure 3 can be seen to be at 25 m/s.

Wind turbines will adjust the angle of the blades using the pitch system, and the direction the wind turbine faces using the yaw system. The wind turbine does this to maintain the maximum possible output for the instantaneous wind speed at a given site. However, regardless of how much or how quickly wind turbines adjust they rarely produce exactly the expected power at every wind speed. Inaccuracies can be due to blade degradation and control errors, so it is expected that wind turbines will deviate from their modelled power curve. And as already stated, the wind turbine's power output depends hugely on the wind conditions and this highlights the importance of accurate wind resource assessment.

At a given site, one wind turbine may not be able to meet the energy production reflected in its power curve, but other wind turbines will comfortably exceed this. Factors affecting a wind turbine's performance can include wind shear, wake effects, turbulence, suitability of the wind turbine for the site, layout of the wind turbines, down-time due to maintenance and alarms or errors in the control system resulting in a shut-down of the wind turbine.

Due to the large number of influences on a wind turbine's performance, an operational power curve for a wind turbine can be significantly different to the manufacturer's warranted one. As a result, on-site monitoring of the power curve can show when a wind turbine is over or under performing.

3.2. Resource Assessment

Wind is constantly changing and this variability of wind stems from how it is created. The Earth's surface receives varying amounts of solar radiation depending on the location. Therefore there are always varying distributions of surface temperature and pressure being produced and as a result, wind is constantly being created and constantly changing.

The variability of wind makes it difficult to predict. Resource assessment is a collection of methods and technologies which are used to estimate the future energy production of a wind farm, but also ultimately how much money the project will earn for its investors.

The importance of an accurate assessment of the wind resource at a site cannot be emphasised too strongly [9]. Accurate estimates of a wind farm's production can be very difficult because wind is so changeable but the wind resource can be the deciding factor as to whether a wind farm gets built or not.

A wind farm's production will depend heavily on the wind conditions at a given site. As the wind resource is constantly changing a detailed understanding of the wind resource at the site is required to produce an accurate Energy Production Estimate (EPE). EPEs are often used by project developers to secure funding from investors for their projects. The wind turbine used at a particular site has a significant impact on the resulting EPE. Measurement techniques are used to establish the wind regime at a site and then different wind turbine types are analysed and compared using specific EPEs for each.

It is desirable to obtain wind measurements that give a true representation of the resource and as a result high levels of accuracy and precision are needed. Much more is required than just calculating the wind speed in a particular place at a particular time and there are rigorous processes in place for resource assessment.

The ability to handle changeable conditions will vary from one measuring device to another. Some devices will excel in specific areas and this makes them more suitable for specific types of measurements.

3.3. Wind Monitoring Technologies

A number of technologies are used for wind monitoring with varying degrees of accuracy. The most common is the mechanical cup anemometer which has been around since the 19th century and the design of three or four spinning cups has barely changed since. An example of this device can be seen in Figure 4.
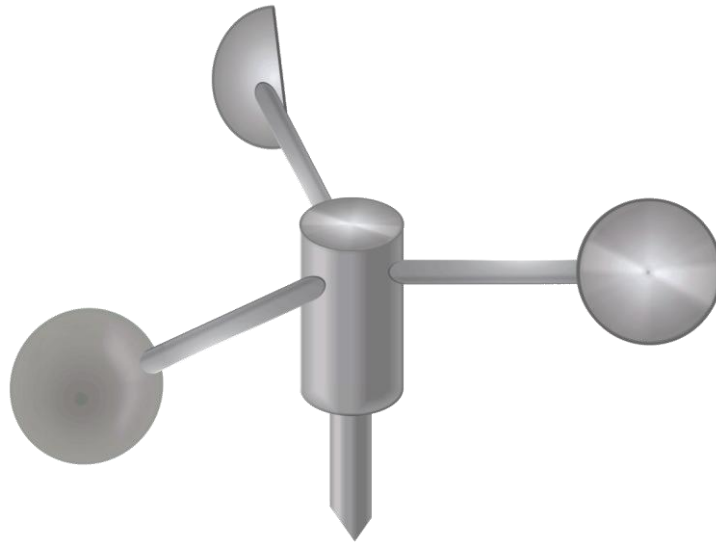
Figure 4: Mechanical Cup Anemometer Example [10]

The mechanical cup anemometer works by the wind pushing the cup around as it flows past the instrument. The movement of the cups produces a voltage. Depending on the speed of rotation this voltage will vary and as a result the wind speed can be calculated. The speed of the cups is what generates the measurement signal.

This device has a number of advantages including its simplicity and that no external power source is required. As well as this, if the dimensions are changed it can be used to measure specific wind characteristics such as turbulence or mean wind speed. It is able to do this because the time and distance constant vary with a change in the size of the cup.

Unfortunately this device does come with disadvantages. Fouling due to dust or ice is common with the moving parts and measurements can only be made in-situ meaning that any obstructions in close proximity can affect the measurements.

The propeller anemometer is similar to the cup anemometer but constantly adjusts itself to face the wind using a wind vane. An example of this instrument can be seen in Figure 5.

Figure 5: Propeller Anemometer Example [11]

The advantage realised by this technology is that there is no need for a separate wind vane but it suffers similar disadvantages due to the moving parts.

Modern Technologies

More advanced technologies came later such as the ultrasonic anemometer developed in the 1970's. This device uses ultrasonic pulses to calculate the wind speed and direction. An example can be seen in Figure 6.
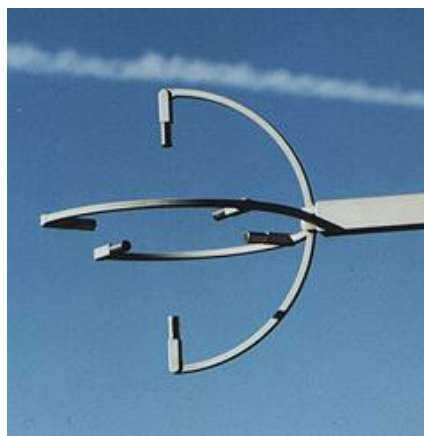
Figure 6: Ultrasonic Anemometer [12]

Depending on the wind direction the wind causes the pulses to accelerate or decelerate and the relative speed of sound is used to determine the wind's characteristics.

This device can vary the speed of the pulses meaning that a large amount of signals can be detected in a short time period. As a result, as well as not having the fouling issues experienced with both the conventional measurement devices (due to no moving parts), this device can accurately measure turbulence with a high resolution within a short time frame.

Meteorological Mast

The technologies explored so far have the capability of measuring instantaneous wind speeds at a given height. From the instantaneous data collected an average wind speed for a given site can be calculated. However, because wind varies with height the accuracy of this assessment is limited to the specific height at which the measurements were taken.

For the resource assessment which is conducted on wind farms, it is important to obtain data at various heights. This is not possible though without multiple devices collecting data at specific heights. This is achieved by a Met Mast, an example of which can be seen in Figure 7.

Figure 7: Meteorological Mast Example

Met masts are widely used onshore and offshore across the wind industry. They vary in design but are often semi-permanent with the ability to be moved and re-used at another site. The height of measurement is obviously limited by the height of the Met Mast tower. In recent times, wind turbine hub heights are increasing and as a result the need for taller Met Masts is increasing.

Met masts are often used as a basis for determining whether a wind farm is worth building or not. The Met Masts are deployed on a specific site to collect wind data for up to two years and based on the data collected it is decided which wind turbines are suitable, and also whether or not the wind farm is worth building at all.

As can be seen in Figure 7, Met Masts can impose a significant visual impact on the surrounding environment and because of this they require planning permission before installation. The visual impact of the Met Mast can also have the effect of creating negative connotations toward the development of the wind farm itself in that area.

Remote Monitoring Technology

Remote wind monitoring devices have been developed as an alternative to the Met Mast, which with its increasing height requirement is becoming more costly and less environmentally desirable. Two examples of these are the SODAR and the LIDAR systems which are discussed in this section.

A Sonic Detection and Ranging (SODAR) system is a device for remote wind monitoring that uses sound waves as a medium for measurement. Conventional wind measurement such as the cup anemometer already discussed measures wind from a point source, but the SODAR system measures wind averaged over an area so it can provide an accurate estimate of the wind resource available for a specific wind turbine.

Laser Detection and Ranging

A Laser Detection and Ranging (LIDAR) device is also used for remote (non-invasive, long range) monitoring but uses an infrared beam as a medium for measurement of wind speed.

LIDAR has been traditionally deployed looking upwards in order to gather a number of measurements at various heights above ground level and has been hugely useful in the wind industry. To measure the velocity of wind, a LIDAR obtains information from a signal which is sent from a transmitter, reflected by a target (the wind) and detected by a receiver back at the source. An example of a LIDAR and SODAR can be seen in Figure 8.

Figure 8: LIDAR and SODAR Example [13]

There are two types of LIDAR measurement, pulsed and continuous wave. Pulsed wave consists of a series of laser pulses and continuous wave transmits a sinusoidal signal of a known wavelength and calculates the phase difference between the transmitted and received signal. Continuous wave systems are far less common than pulsed wave systems.

The conical scan which emits from the LIDAR allows it to facilitate multiple readings at different angles allowing wind characteristics to be established such as the horizontal and vertical components of the wind vector as well as direction. The three-dimensional coordinates of the wind are calculated from the difference in time between when the beam was emitted and returned, the angle at which the beam was emitted and the absolute location of the sensor above the surface of the Earth.

The reliability of any chosen device must be considered. This is the capability of the device to continually produce results to the same degree of accuracy over a long period of time. This can be affected by issues such as weather and the elements, calibration errors or simply device wear and tear. LIDAR for example has a high sampling rate and results are provided at a very high resolution, however errors can occur under bad weather conditions such as rain and snow.

4. Theoretical

This section explains why this thesis was conducted, discusses the reasoning behind it and explores solutions to some of the issues faced by the wind industry.

4.1.　Uncertainty in Wind Measurement

Wind speed is a critical measurement characteristic in terms of the economics of a wind farm. Like all weather conditions, wind is relatively difficult to predict and therefore introduces a high level of uncertainty into any predictions that are associated with it.

Uncertainty in the measurement can lead to an under or over prediction of annual energy production and this poses a significant financial risk to any project. The wind industry has adopted a number of procedures including selection, calibration, deployment and use of anemometry to minimise uncertainty [9].

For a wind project the common approach is to capture wind data from a Met Mast which is strategically placed somewhere on the wind farm. The wind speed and conditions at the different wind turbine locations are then approximated taking into account the site specific terrain and potential wake effects from other wind turbines. The uncertainty associated with these approximations is known as "space-domain" uncertainty and is the result of the predictions not accurately representing the location of the wind turbines but instead being a reflection of the Met Mast location. This same space-domain uncertainty can be experienced when predictions of wind speeds above the height the instrumentation measuring the wind are made. Additional uncertainty is brought by the reality that the wind measurements do not accurately represent a full life cycle of a wind project and are largely based on one or two years of wind data. This type of uncertainty is known as "time-based" uncertainty.

Numerous developments in statistical and mathematical techniques to improve long term projections have been developed but time-domain uncertainty is still difficult to reduce. In comparison, significant reductions have been seen in space-domain uncertainty due to the development of new technologies which more accurately assess the flow of wind across a site [14]. Any reduction in uncertainty is significant as it

impacts the annual energy production estimate and this can heavily impact a project's justification.

For many years the Met Mast has been the method used for wind measurement at a wind farm but the limitations of the Met Mast allowed for the emergence of remote sensing solutions such as the LIDAR and SODAR which are laser and acoustic based measuring instruments. These remote sensing solutions are simple and easy to deploy in different desired locations. By placing these portable measurement instruments at the wind turbine locations it is possible to reduce the space domain uncertainty that would be associated with the Met Mast measurement if it were not present.

4.2.   The Emergence of LIDAR

For a number of years now remote sensing solutions such as LIDAR have competed with Met Masts for wind monitoring as they provide a number of benefits. Some of the main advantages are discussed in this section.

LIDARs have been used in industry now for a number of years because they offer a high degree of accuracy. They have developed to now using two degrees of freedom, both azimuth and elevation, instead of only one. Doing this allows the LIDAR to measure anywhere within the range of the LIDAR instead of being limited to wind which is immediately above it (like a Met Mast).

Unlike a Met Mast, LIDARs do not need large towers and foundations to allow them to measure wind at specific heights. This advantage is twofold. LIDARs are portable so can be moved around easily on site to measure at different locations. In addition, the planning permission which a Met Mast requires for its large tower is not needed for LIDAR. A number of LIDAR instruments can be deployed onsite without the need for planning permission.

LIDAR offer advantages in measurement too. LIDAR measure up to and above the specified hub height of a wind turbine, and instead of modelling complex terrain in the vicinity of the LIDAR it now directly measures the differences in the wind stream.

For the last ten years studies have been conducted to compare the measurement of LIDAR and cup anemometry. For example in 2004, when LIDARs were first tested for wind measurement a campaign using a ZephIR (LIDAR) was conducted. It was argued that the measurement produced by the LIDAR was accurate but the errors which arose led to uncertainty over what was actually moving at the velocity calculated [15]. Cloud and mist can contribute to the Doppler signal which the LIDAR measures so can lead to overestimation of wind speed. As a result, cloud correction algorithms are now included in the technology's measurement. Since then, many more measurement campaigns have been conducted and it is clear that accuracy is improving through the introduction of new technologies such as the windcube for example. This technology is explained in greater detail in section 5.

Since their inception, LIDARs have proven accurate and have been successful in overcoming a number of pitfalls with the commonly used Met Mast. That is not to say however that they are without fault. This thesis sets out to explore these advantages and to assess whether LIDAR could be considered as an alternative wind measurement instrument to a Met Mast.

In order to complete the primary objective of the thesis and confirm the accuracy of LIDAR, it was proposed that a test campaign be conducted whereby LIDAR data was compared to that of a Met Mast. Further details behind the measurement campaign conducted are included in the Experimental and Discussion of Results section.

4.3.   Power Performance Testing

The power performance of a wind turbine describes the correlation between the free-inflow wind speed and net electrical power output of the wind turbine. It is a significant input into predicting the annual energy yield of a wind farm which is the deciding factor on whether a wind farm will be built or not. With the drive for reduced costs in the offshore wind sector, one area of importance where LIDAR can offer a potential saving is with the PPT which is conducted on a wind turbine.

There are significant financial implications if a wind turbine is not producing as much power as was predicted in the financial model and this usually relates to an unrealistic power curve. A PPT is used to verify a wind turbine's performance and without the test a claim on the contractual agreement is unlikely to be successful. As well as for

claims against unrealistic power curves, the PPT is also used by the wind turbine supplier for the certification process.

When compared to onshore wind, offshore wind farms are associated with a higher financial investment. It is also a newer technology so there is a higher technical risk and the wind conditions offshore are not as well known. As a result PPT is more rather than less important. However due to the expense associated with the IEC compliant tests, which need Met Masts requiring piling and foundation structures, they are conducted less rather than more often.

The secondary objective of this thesis investigates if there is the potential to reduce wind farm costs by using LIDAR instead of the current more expensive alternatives.

Currently European IEC standards state that Met Masts must be used for the PPT of a wind turbine. These have recently been updated to include the use of LIDAR; however this is only in conjunction with a Met Mast and cannot be conducted solely by LIDAR. To perform an IEC compliant PPT, there is a requirement to measure wind speed upwind of the wind turbine at height a minimum of 2.5 times the rotor diameter away [16]. This is displayed in Figure 9.
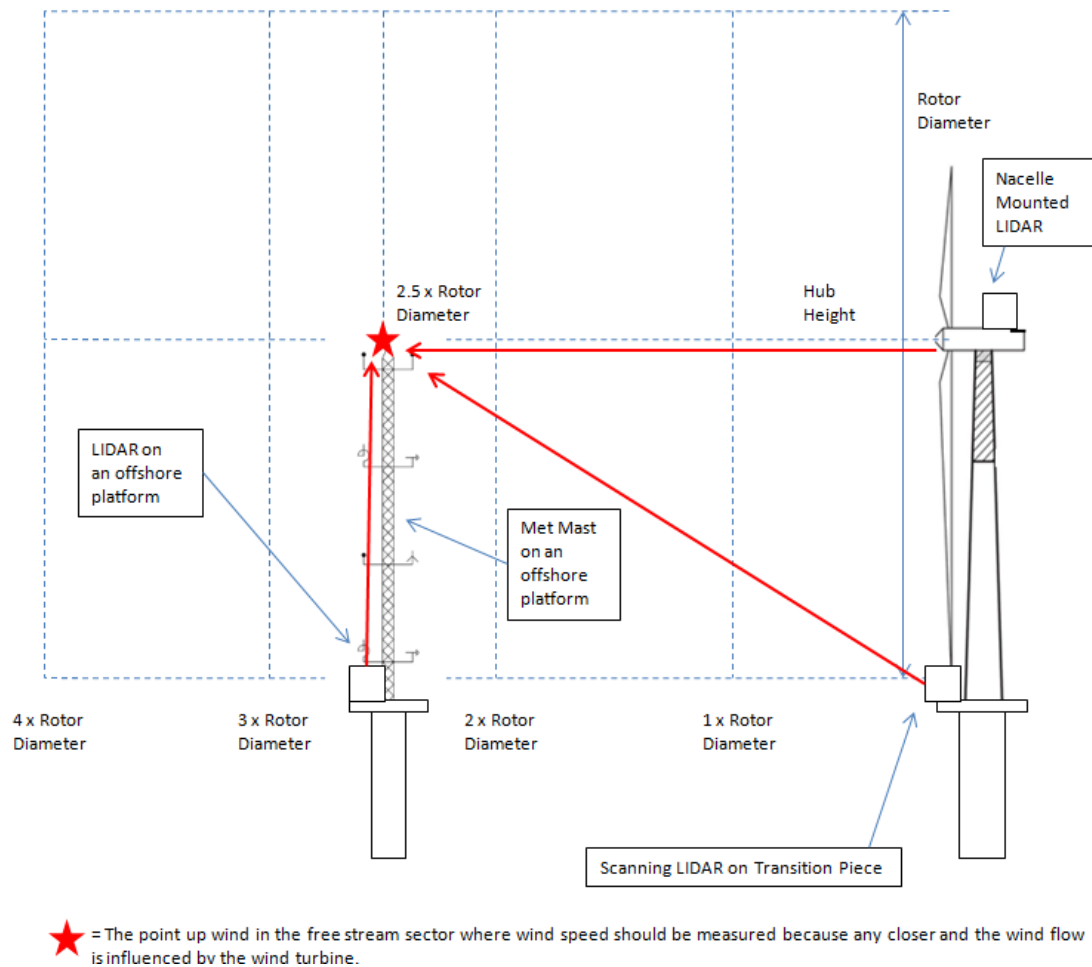
Figure 9: Measurement Height/Distance According to IEC Standards

Also displayed in Figure 9 are the alternative options for measuring at this point which LIDAR make available. These include a forward facing LIDAR attached to the wind turbine's nacelle, a LIDAR on an offshore platform and a scanning LIDAR on an offshore wind turbine's Transition Piece (TP). Table 1 displays the current stance and potential future use of LIDAR.

Table 1: Comparison of Met Mast to LIDAR Alternatives

	Met Mast	Platform LIDAR	Floating LIDAR	Nacelle LIDAR	SCANNING LIDAR
Control anemometry available [IEC]	YES	YES	NO	NO	NO
Ground based measurements [IEC]	YES	YES	NO	NO	YES
Measures conditions across entire rotor disc	NO	YES	YES	NO	YES
Established track record of accepted data	YES	YES	NO	NO	YES
Standard calibration procedure	YES	YES	NO	NO	YES

Floating and nacelle mounted solutions are explicitly excluded by current IEC standards, which state "only ground based remote sensing devices are used" [16]. Only LIDARs situated on the TP of the test wind turbine or on fixed platforms comply with this IEC requirement. The LIDAR option on the TP was selected to be taken forward for further analysis as part of this thesis. This option is not affected by tower sway, the beam is not obstructed by the passing blade, wind shear data across the entire rotor can be measured and there is no requirement for additional infrastructure for the installation.

With the need to reduce costs, developers are looking at areas where savings can be made and in some instances the requirement for Met Masts is being questioned. If LIDAR can perform the same function it is likely that we will see the emergence of more LIDARs being employed in the wind industry especially for offshore wind farms.

This thesis explores firstly the need for a PPT, but also the potential to use LIDARs for this purpose in the drive to reduce costs for the wind industry. A PPT has been conducted at an offshore wind farm using a Met Mast and the results are discussed in Section 7.2. If time scales allow the same test will be conducted using a LIDAR on a TP and a comparison of the results will be made.

5. Experimental

This section describes the process behind achieving the project's main objectives which have been established in the previous section.

In order to complete the primary objective of this thesis and confirm the accuracy of LIDAR, it was proposed that a test campaign be conducted whereby LIDAR data was compared to that of a Met Mast. It was expected that by completing this measurement campaign with both the LIDAR and Met Mast measuring at the same time that the results would show that the LIDAR is as accurate as the Met Mast. The study would then be able to justify stand-alone remote sensor wind monitoring.

The study was undertaken at a Test site located 30 miles west of Glasgow in Scotland. The site has excellent exposure to the prevailing south westerly wind and has a low surface roughness.

5.1. Met Mast Details

A reference Met Mast is installed at the site for the purpose of verifying the wind climate experienced by the wind turbines which are also installed at the site. An example of a Met Mast can be seen in Figure 10.

Figure 10: Reference Met Mast for Measurement Campaign

The instrumentation installed on the Met Mast is detailed in Figure 11 along with that of the LIDAR and substation.
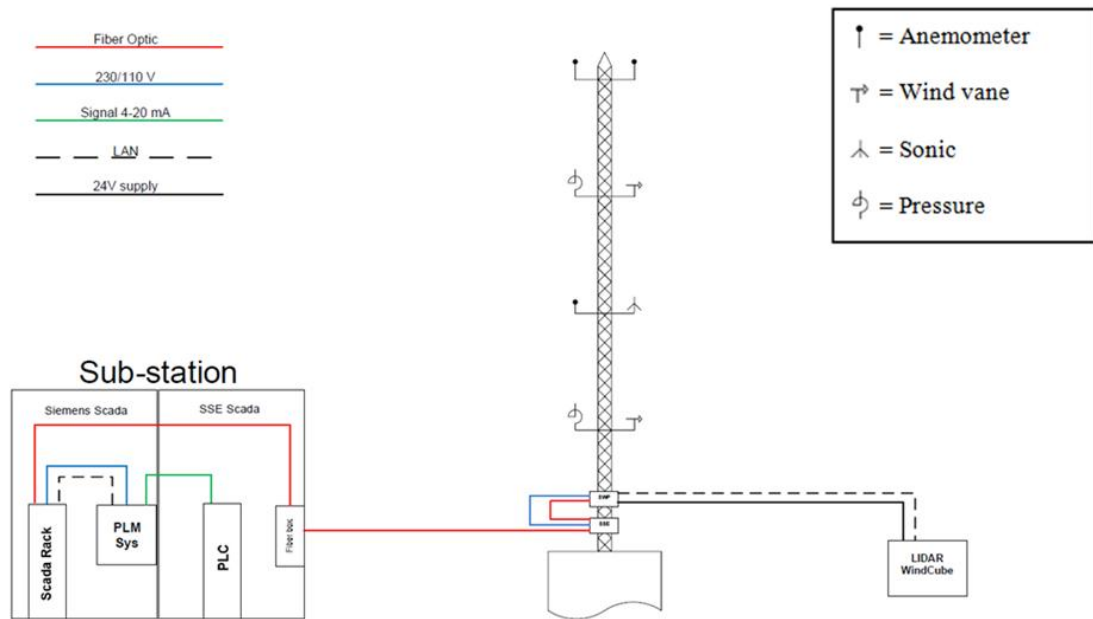
Figure 11: Onsite LIDAR and Met Mast Configuration Schematic

As can be seen in Figure 12, the LIDAR and Met Mast are separated by approximately 5 meters and the substation and the Met Mast by approximately 12 meters.
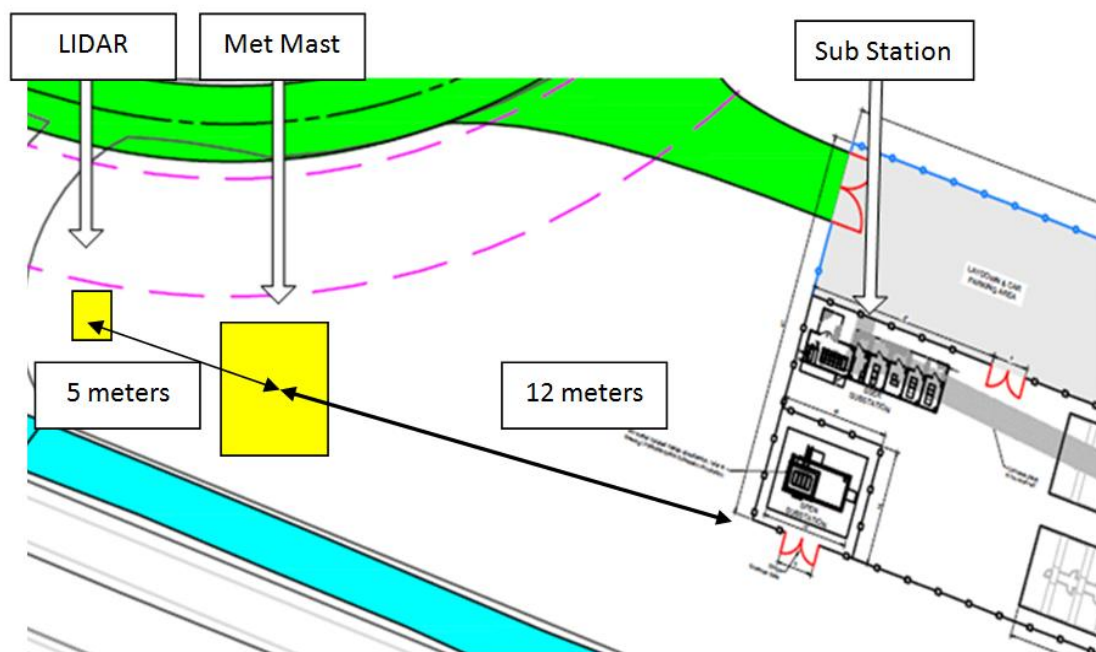

Figure 12: Onsite Location of Equipment

5.2. LIDAR details

The LIDAR installed was a windcube LIDAR manufactured by Leosphere and supplied by Natural Power (UK). The reason this was chosen is because it is considered highly accurate, it is compact (55 x 55 x 55cm), it is light at only 40 kg, only consumes 45 W and has no moving parts so is more reliable.

Further details on the LIDAR's specifications are detailed in Table 2.

Table 2: Windcube v2 Specifications [17]

Leosphere Windcube v2	
Range	40 to 200m
Data sampling rate	1s
No. of programmable heights	12
Wind speed accuracy	0.1 m/s
Wind speed range	0 to +60 m/s
Directional accuracy	2°
Dimensions L-W-H	543 x 552x 540 mm
Weight	45 kg
Power consumption	45 W nominal
Temperature range	-30°C to +45°C/-22°F to 108°F
Operating humidity	0 to 100% RH
Housing classification	IP67 (for inner racks)

The LIDAR is powered from the distribution terminals inside the Met Mast cabinet as can be seen in Figure 13.

Figure 13: Onsite Power Supply for LIDAR

The LIDAR was installed on a ground slab to provide a level platform and for security reasons the LIDAR was surrounded by a fence as can be seen in Figure 14 and Figure 15. This had no influence or bearing on the data or analysis so all potential blocking of the LIDAR's beam was avoided.

Figure 14: Onsite LIDAR Arrangement

Figure 15: Onsite Security Fence Protection for LIDAR

5.3. <u>Measurement Campaign</u>

A Campbell Scientific CR1000 logger was used to log data for the Met Mast. The LIDAR data was captured in a similar way. The LIDAR was able to patch into the fibre run in the patch panel inside the Met Mast enclosure. The signals from the Met Mast and from the LIDAR were then transferred via analogue output modules and the logged data was then accessed using the Supervisory Control And Data Acquisition (SCADA) system. The data could then be downloaded in an excel file and used for this study.

The measurement height for both the LIDAR and Met Mast was set at 110 meters and they were programmed to record for every 10 minute period; the mean, maximum, minimum and standard deviation of wind speed from each anemometer, and the mean

and standard deviation of wind direction from each wind vane. All anemometers were individually MEASNET (Measuring Network of Wind Energy Institutes) Calibrated. The results from the measurement campaign are discussed in section 6.

5.4. Power Performance Test

An offshore PPT was conducted to assess the value it added to a wind project. Following this the installation of LIDAR was completed with the intention that the same PPT would be completed so the results could be compared.

A PPT was performed on a wind turbine at a wind farm off the coast of the south west of England. The method used is described in the IEC standard 61400-12 Power Performance Testing [16]. The power curve is determined by collecting simultaneous measurements of wind speed and power output.

The power output of the wind turbine was measured using the equipment on the wind turbine and obtained through the SCADA system. A Met Mast installed adjacent to the wind turbine being tested was used to perform the test and measure the wind speeds. The wind turbine and Met Mast layout for the PPT is displayed in Figure 16.
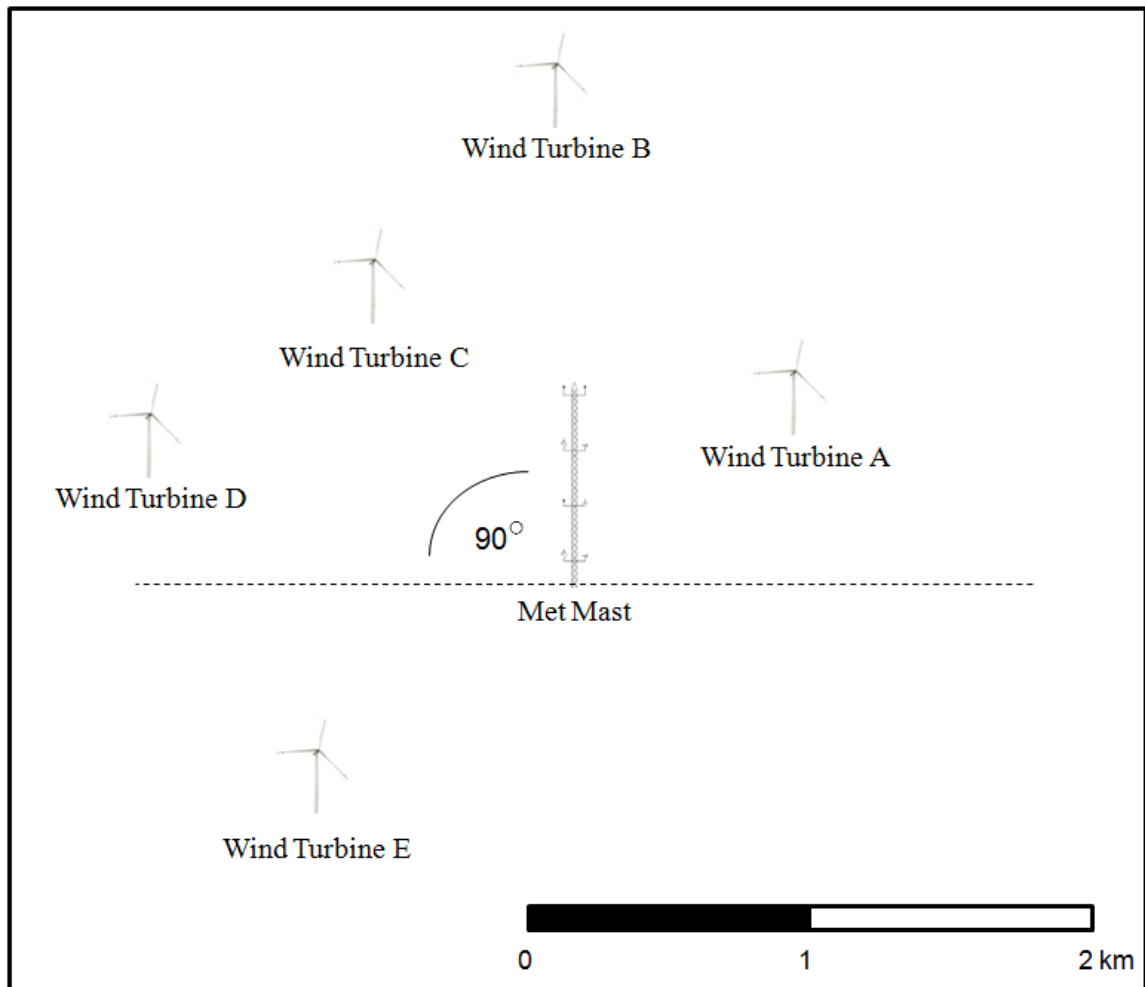
Figure 16: Wind Farm Layout

The PPT was conducted in August 2012 and concluded in November of the same year. The power output from the wind turbine was collected and associated with 1 m/s bins of wind velocity. Corrections were made to increase the accuracy of the results and these are discussed in the following sections.

Wind Direction

It is vital that the wind direction of the measurement equipment align. To test this, data was collected from the Met Mast and from the wind turbine and then graphed to compare the results. This can be seen in Figure 17.
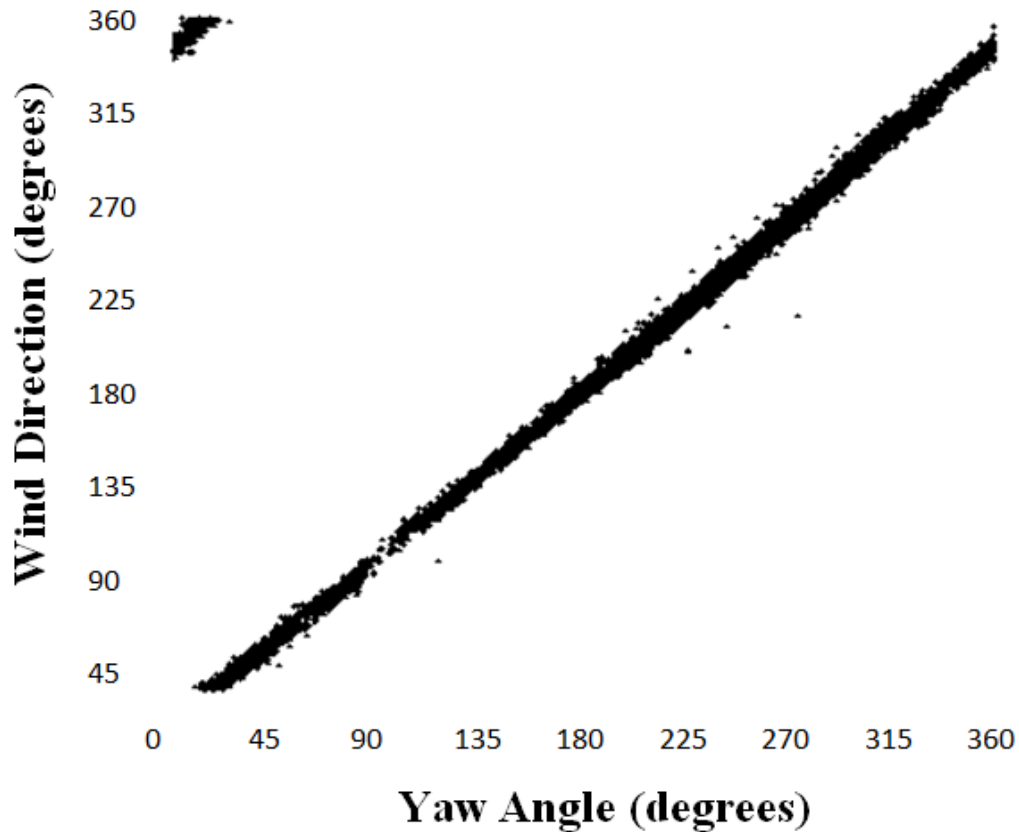

Figure 17: Met Mast Direction Data plotted against Yaw Angle of the Wind Turbine Data

As can been in Figure 17 the wind directions at the Met Mast and the yaw angle of the wind turbine correlate well. Misalignment between the wind turbine yaw direction and the free stream wind would have a significant effect on both the wind turbine's

performance and the operating lifetime of wind turbine, due to the potential increase in loading from the wind.

An offset of approximately 20 degrees can be observed in Figure 17 but this is not unusual. 0° will generally refer to the direction in which the wind turbine was facing during its most recent reset.

To assess the accuracy of the data, vortex hindcast data was used as a comparison. This is modelled data which uses satellite measurements as a basis [18]. When Mat Masts are not yet available at wind farms it is not uncommon to use vortex hindcast data to produce preliminary models of the wind resource available at a site. As can be seen in Figure 18 the correlation is not as good as in Figure 17. The Met Mast data is therefore more accurate and as a result was used for the PPT instead of the vortex hindcast data.
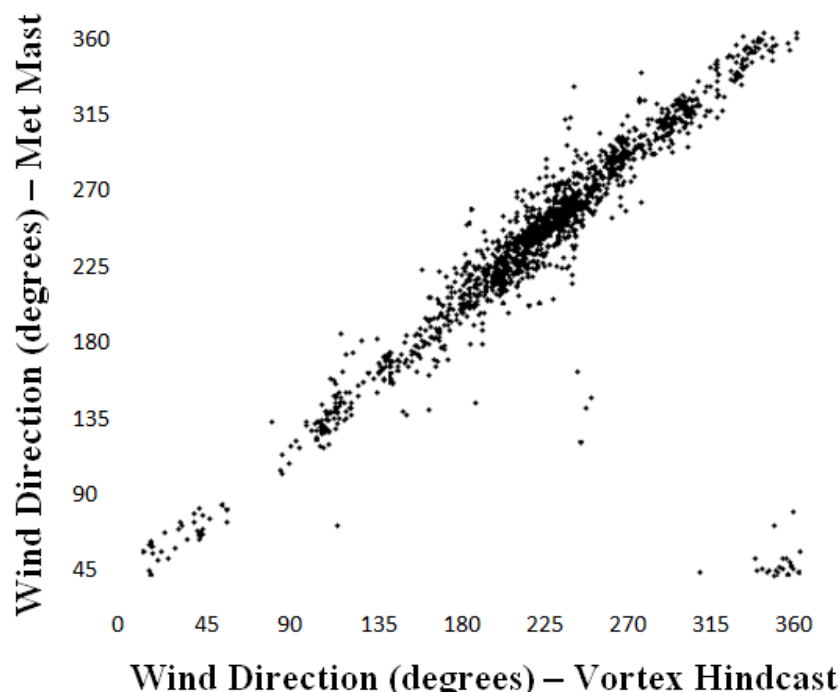

Figure 18: Direction Data for the Met Mast plotted against Vortex Hindcast Data

PPTs are performed on wind turbines adjacent to Met Masts and usually this location is on the periphery of a wind farm. The reason for this is because in this location the Met Mast and wind turbines being tested are least affected by wake effects from other wind turbines.

To perform the PPT a range of wind directions for the wind turbine and Met Mast needed to be established. The ratio of the wind speeds recorded using the Wind Turbine (WT) equipment was plotted against those recorded by the Met Mast (MM) and can be seen in Figure 19.
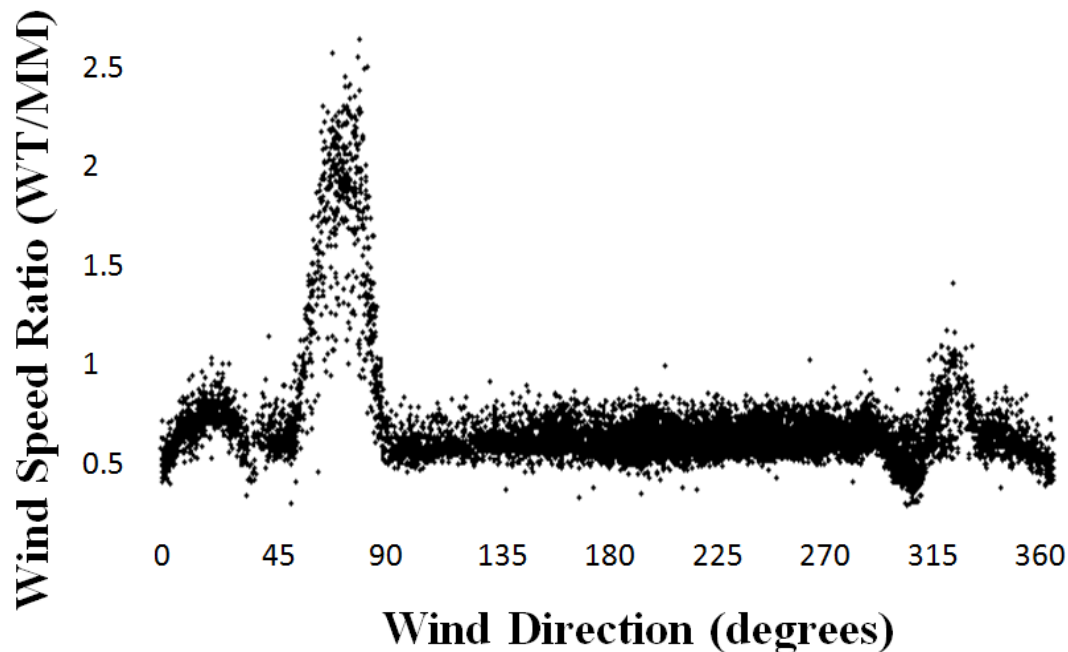

Figure 19: Wind Speed and Direction Data for Wind Turbine plotted against Met Mast Data

The scatter displayed in Figure 19 is due to the inaccuracy of nacelle anemometers as they are positioned behind the wind turbine's rotor. The moving rotor has an effect on the wind before it is measured by the anemometer and this effects the accuracy of the results measured. It can also be seen in the plot that there is a significant wake effect

on the Met Mast from the adjacent wind turbines B, C, D and E between 270° and 90°. This can also be seen in Figure 16. As discussed, it is important to use a wind direction for a PPT which is not significantly affected by wake effects and because of this the range from 130° to 270° was chosen for the test.

Correction for air density

Air density has a significant impact on a wind turbine's output and because of this it is important to take account of it in a PPT. The ten-minute wind speeds recorded by the Met Mast during the PPT were adjusted to align with the air density in the power curve. The values for the pressure and temperature which were measured at the Met Mast were confirmed consistent with the vortex hindcast data and used for the evaluation.

Wind Turbine Operation

To improve the results, periods where the wind turbine was not generating were filtered from the analysis. The wind turbine was assumed to be unavailable if it was producing less than 1% of its rated capacity (<36.36kW) in wind speeds above its specific cut-in (3 m/s) wind speed. To confirm that the wind turbine was in fact unavailable during these times, the power output for the wind turbine was plotted against the rotor Rotations Per Minute (RPM) and this can be seen in Figure 20.
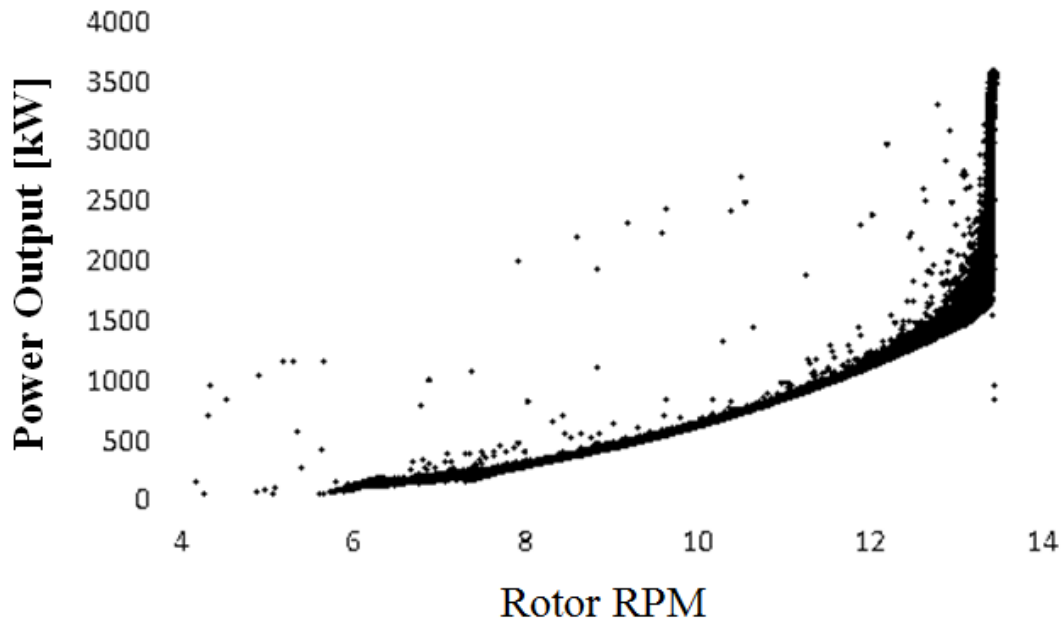
Figure 20: Wind Turbine power output versus Rotor RPM

It can be seen in Figure 20 that this wind turbine is a variable speed machine. This means the wind turbine can produce power across a range of wind speeds and is not fixed to one wind speed. The wind turbine starts producing at its cut-in wind speed of 3 m/s up until cut-out at 25 m/s. The black line illustrates this where it can be seen starting just before 6 m/s and then regulating its RPM using its pitch system it ramps up to its rated wind speed of approximately 14 m/s where it flattens out. Outside of this distinct black line there are only a small number of outlying ten-minute periods. This gave confidence that no further processing of the data was needed.

Power Curve Binning

The measured data for the ten minute periods were averaged to 1 m/s bins and were then used for comparison with the warranted power curve. This is shown in the Table 3.

Table 3: Measured Data versus Warranted Power Curve Data

Wind Speed (m/s)	Warranted Power (kW)	Mean Measured Power (kW)
0	0	-32
1	0	-31
2	0	-33
3	0	-10
4	130	73
5	274	202
6	505	418
7	825	706
8	1240	1146
9	1776	1666
10	2403	2336
11	3045	3056
12	3501	3505
13	3622	3582
14	3636	3594
15	3636	3602
16	3636	3594
17	3636	3560
18	3636	3603
19	3636	3601
20	3636	3603
21	3636	3600
22	3636	3579
23	3636	3600
24	3636	3513
25	3636	2795

Table 3 clearly shows the wind turbine is under performing when you compare the warranted values with the measured values. It can also be seen in Table 3 that when the wind turbine is not producing power in wind speeds below cut-in, it experiences parasitic loads in the region of 30 kW. This is quite normal as power usually needs to

be supplied to maintain the wind turbine when it cannot use the wind to maintain itself. However, given the underperformance in the rising part of the power curve these loads may be having more of an effect that normally expected.

Offshore LIDAR installation

The installation of a LIDAR instrument was completed with the intention that the same PPT would be completed and the results could be compared to those captured by the Met Mast which has already been discussed. Unfortunately due to time restraints it was not possible to complete the measurement campaign with the LIDAR system but the installation was completed and details are included in this section.

The following section describes the installation of a windcube LIDAR on an offshore wind turbine's TP. Figure 21 shows the location of the windcube on the wind turbine's TP.
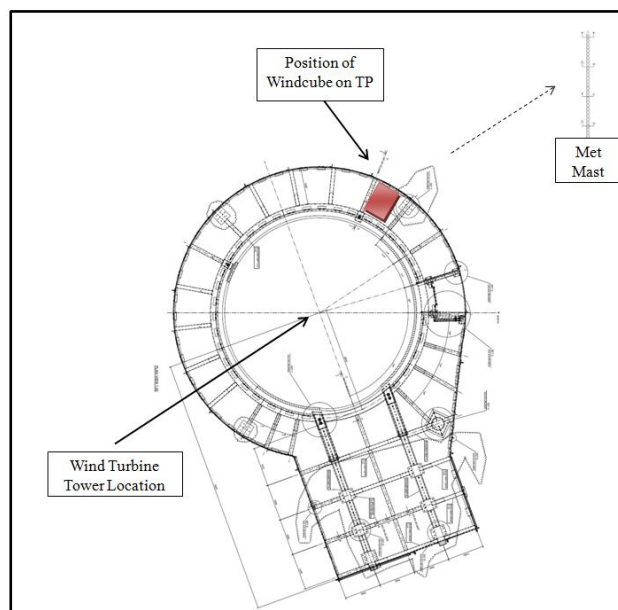

Figure 21: Plan View of LIDAR on Offshore Wind Turbine Transition Piece

The TP was chosen because the wind cube requires a stationary location to make accurate measurement. As can be seen in Figure 21 the LIDAR has been located adjacent to the neighbouring Met Mast. Locating the LIDAR adjacent to the Met Mast will enable a comparison to the data measured by Met Mast and provide evidence that the LIDAR is a valid measurement device for a warranted PPT. Figure 22 shows the location of the Met Mast in the background and the location of the LIDAR in the foreground.

Figure 22: Location of LIDAR on Offshore Wind Turbine Transition Piece

To accurately achieve the correct orientation of the windcube LIDAR which was used the values in Table 4 were input into the LIDAR controls. In Table 4 the LIDAR type and measurement heights are highlighted.

Table 4: LIDAR Values

Device Location			
Height above LAT (m)	Orientation with respect to True North (º)	Wind Direction Correction Factor (º)	Comment
42 m	+15°	+48°	So you have to subtract 33° from the wind direction in order to get the correct value

Device Identification								
	Type	Serial	Year	Software Version	IP Address	Time Base	Prisma Angle (deg)	Comment
Device Identification	Windcube WLS7 V1.2	WLS7-58	2009	3.1.62	129.175.131.4	UTC +0	27.89	

Measurement Parameters										
	Meas. Height 1 (m)	Meas. Height 2 (m)	Meas. Height 3 (m)	Meas. Height 4 (m)	Meas. Height 5 (m)	Meas. Height 6 (m)	Meas. Height 7 (m)	Meas. Height 8 (m)	Meas. Height 9 (m)	Meas. Height 10 (m)
Relative to LIDAR	40	47	53	57	60	68	76	81	108	138
Relative to LAT	82	89	95	99	102	110	118	123	150	180

The stability and direction of the LIDAR were first confirmed manually. The stability was confirmed using the level which is attached to the LIDAR device. This can be seen in Figure 23 and clearly displays alignment.

Figure 23: LIDAR Stability Confirmation

The direction was also manually confirmed using a compass to compare to the arrow pointing North on the LIDAR device. This can be seen in Figure 24.
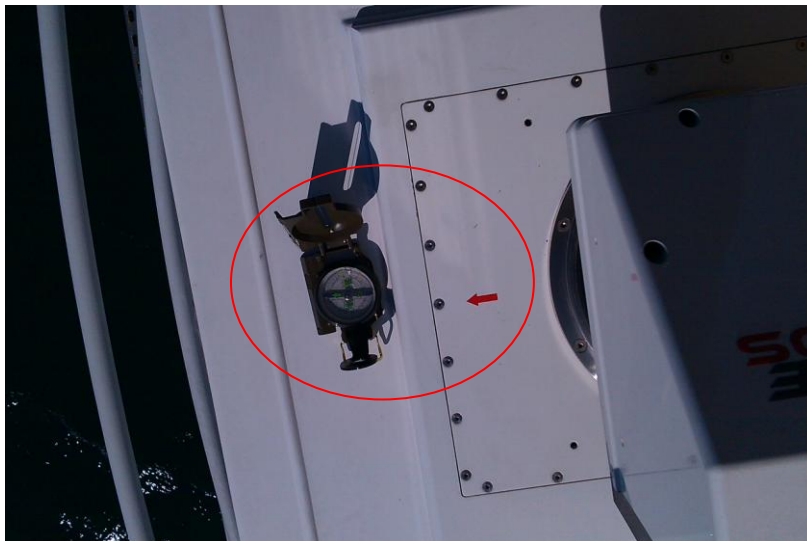

Figure 24: LIDAR Direction Confirmation

Logging into the LIDAR system further confirmed that the device was installed correctly. It can be seen that the wind speed and direction profiles are clearly aligned in Figure 25 and this shows the device was also calibrated correctly.
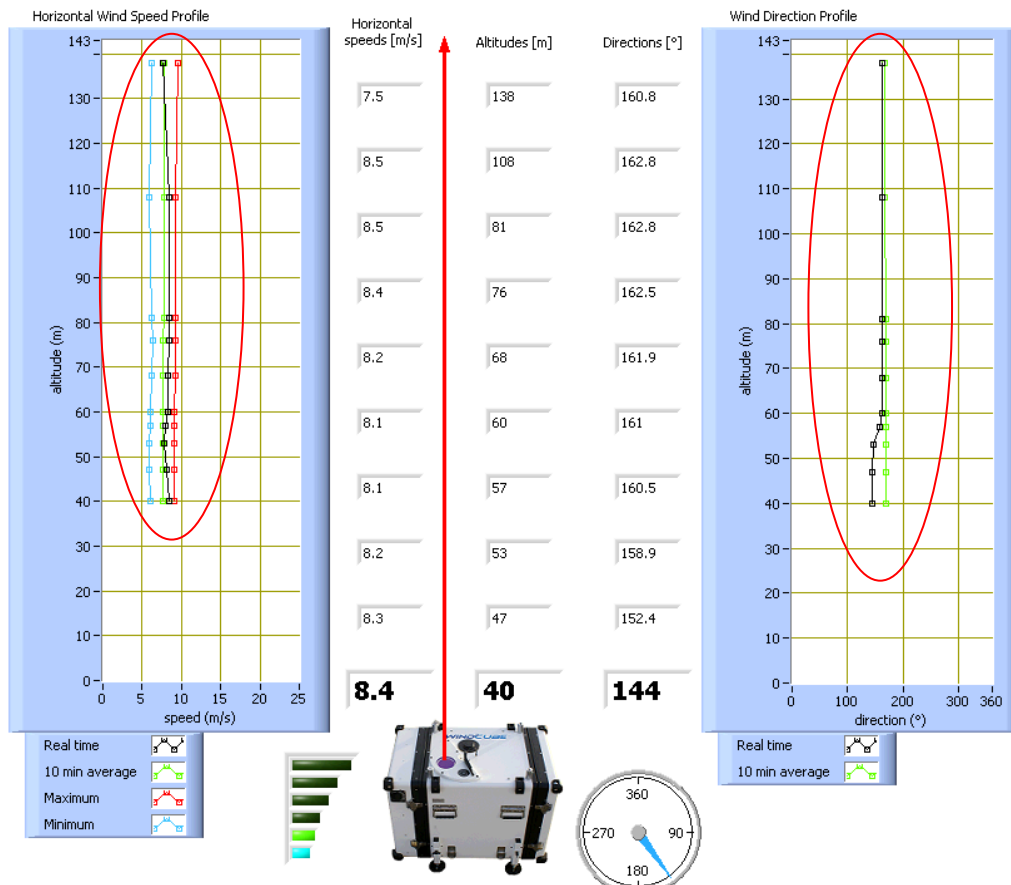

Figure 25: LIDAR Wind Speed and Direction Profiles

Logging in the control system for the LIDAR would also confirm the status of the system and if it was correct. The observed settings are displayed in Figure 26 and Figure 27.
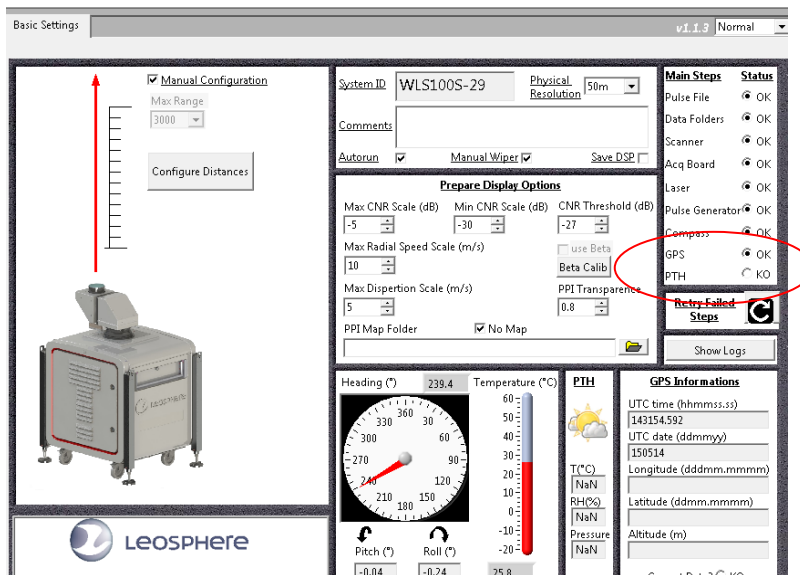
Figure 26: LIDAR Setting 1

It can be seen in Figure 26 that the PTH value status was not ok. This is associated control path (PTH) and means the system could not establish normal operation and was constantly restarting. A wiper issue was also observed in Figure 27 and it was thought that it this was likely root cause of the restarting issue. A solution to these issues is discussed in section 7.2.
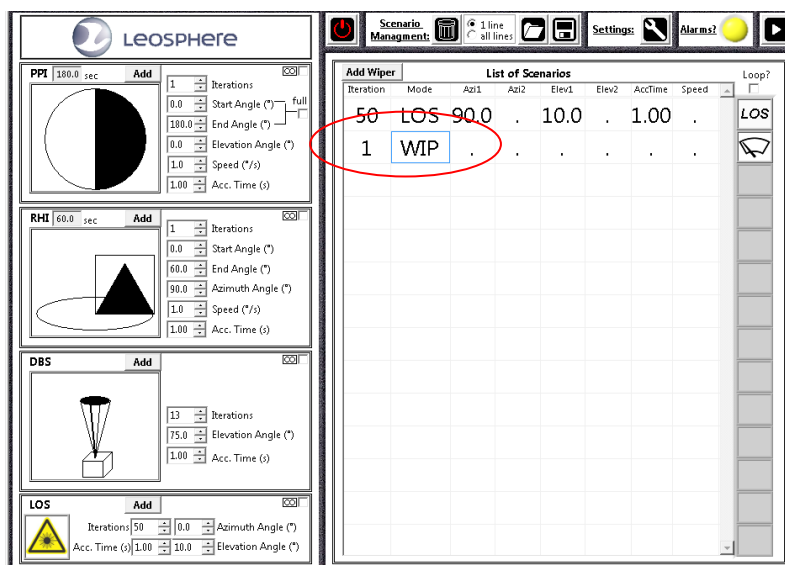

Figure 27: LIDAR Setting 2

6. Discussion of Results

This section looks at the results and uses them to establish a conclusion from the work which was conducted.

7.1. Measurement Campaign

The overall conclusion which can be taken from the measurement campaign conducted is that the LIDAR and Met Mast correlate well and that either form a technology could be used for wind measurement.

Wind data was recorded by both the LIDAR and Met Mast for wind speed and direction. The data produced by both were quality checked, and suspect data flagged and not included in the following analyses. In Figure 28 the wind speed measurement is compared.
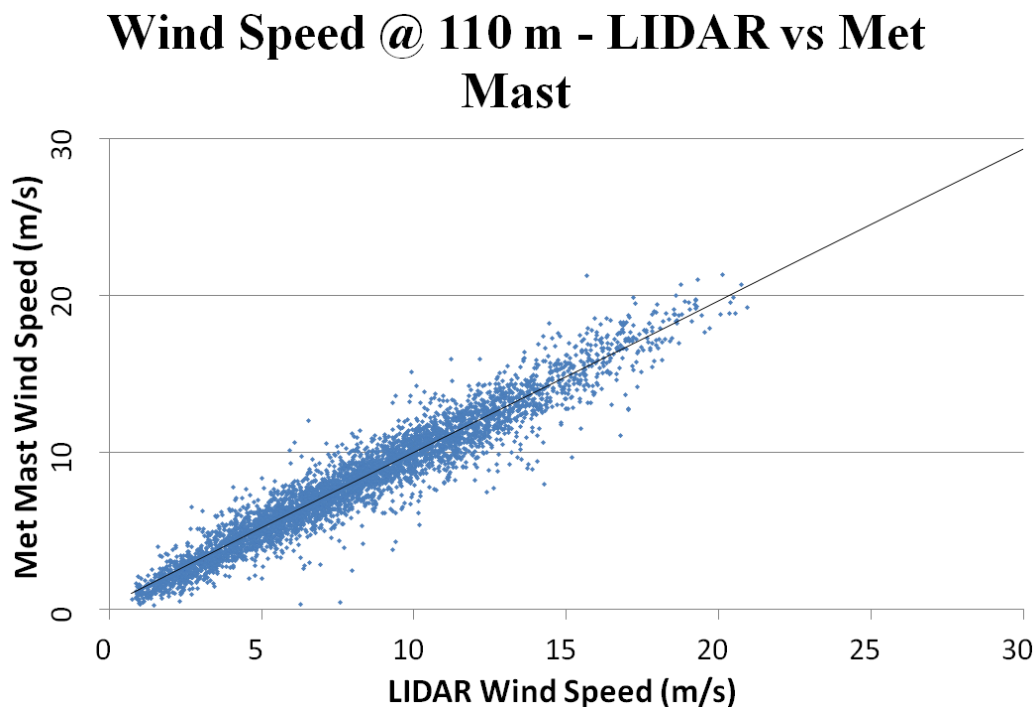

Figure 28: Wind Speed Data for Met Mast Plotted against LIDAR

As can be seen in Figure 28, wind speeds from approximately 0 m/s up to approximately 25 m/s were measured and are shown on the graph. Figure 28 displays the favourable correlation between the measurements by the two technologies. Using the standard regression method of a best fit line produced a 93% correlation shown by the line in Figure 28. This is an acceptable level of correlation given the limited amount of wind data collected. A greater correlation in the late 90's would be expected with further filtering of the data and a longer measurement campaign which are discussed in section 6 and 8.

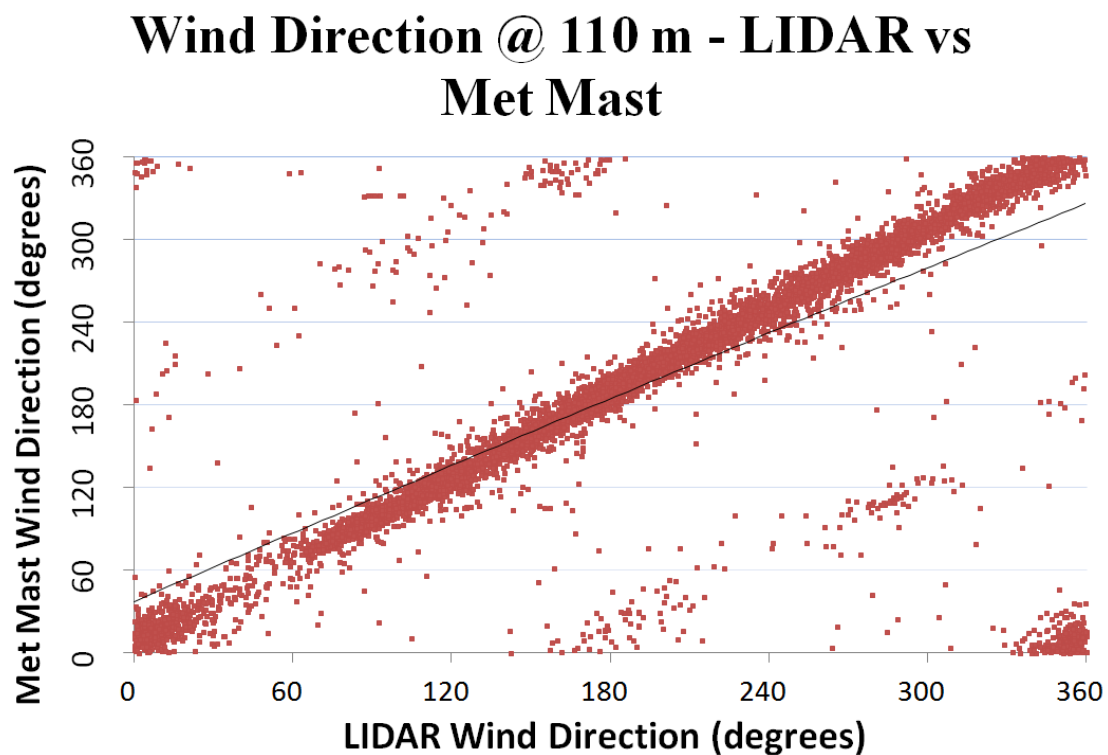The wind direction from the Met Mast and LIDAR are included in Figure 29.

Figure 29: Wind Direction Data for Met Mast Plotted against LIDAR

The results here show more variance but overall there is a general agreement between the two measurement devices. The obvious line can be taken to confirm the known south westerly prevailing wind direction.

There are clear deviations in Figure 29 too and these could be for a number of reasons including weather, terrain, sensor erros and measurement techniques. Heavy rain and fog can also have a significant effect on LIDAR measurements. Although the LIDAR was located adjacent to the Met Mast, terrain effects may be the cause of some of the scatter. Anemometer sensor degradation could be the case of some of the deviations or the method of measurement which is volume in the case of LIDAR versus point measurement in the case of the Met Mast.

In general a good agreement has been found between both sets of data when comparing 10 minute averaged measurement. The measurement campaign has confirmed that LIDAR is an accurate form of measurement and both methods could be used to provide accurate real time data input for wind power forecasting models or for a PPT.

7.2. Power Performance Test

The overall conclusion of the PPT is that it provides an accurate assessment of a wind turbine's performance and it is a valuable test which all developers should look to perform at their wind farm sites.

The PPT performed shows that there was a shortfall of 3% in energy capture during the period used for the calculation. The PPT shows that the wind turbine is not performing to the agreed level outlined by the warranted power curve. Figure 30 displays the results from the PPT.
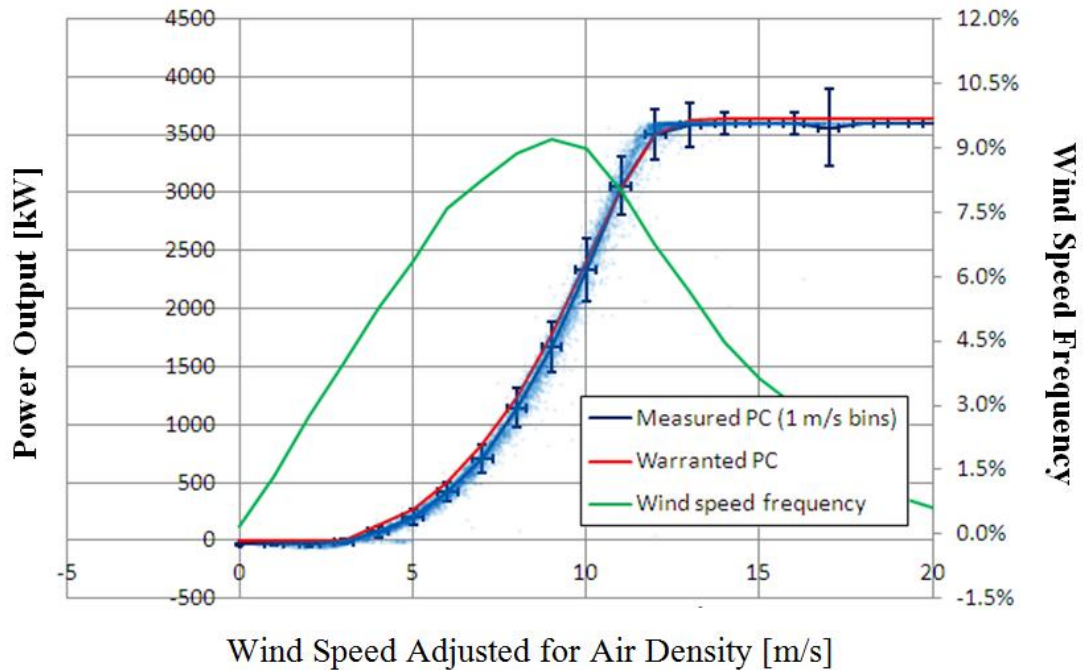

Figure 30: Power Performance Test Results

It can be seen that the general pattern follows the warranted power curve but does not follow it exactly. This shows the difficulty in the accurate prediction of energy production.

It can be seen that the main deficit in performance, approximately 90%, is in the rising part of the power curve up to 10 m/s. The remainder is due to the wind turbine's power output reaching a maximum of 3600 kW and not the warranted maximum of 3636 kW.

There is will always be some error associated with a PPT even when extensive measurement campaigns are assessed the final error can exceed 10% [19]. This can be seen in Figure 30 where the error bars represent the standard deviation of the data in each bin. For this reason it is recommended that a formal independent PPT is conducted as per the wind farm supply contract. The results of which can then be used to negotiate with the wind turbine supplier for lost revenue as the wind turbine is not performing to that which was described in the warranted power curve. In parallel a PPT should be conducted using LIDAR technology. Both Scanning LIDAR and forward facing nacelle installed LIDAR could also perform the test and the results could be compared.

Offshore PPT

Unfortunately due to delays associated with contracts, weather and the duration of time required to perform a PPT (the time to capture enough wind measurements in all directions) did not elapse. However, it was possible to install the LIDAR in the offshore location as described in Section 5. Following the installation of the LIDAR there were some issues with the windcube and some trouble shooting was required. This section describes some of the issues faced and how they were solved.

It transpired that the wiper function to clear dirt, rain etc was faulty and was causing the device to restart the instruments every time it was initiated. Pop ups appeared on the LIDAR control system. Examples of these are displayed in Figure 31.
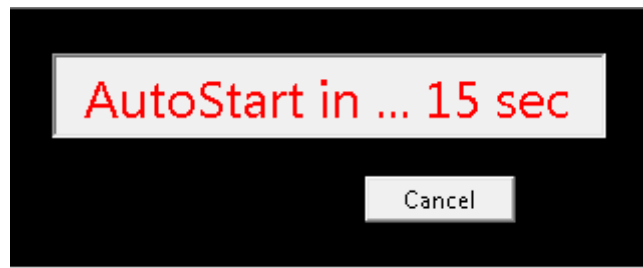
Figure 31: Offshore Installation Trouble Shooting

Remote connection was established with the LIDAR system and this meant it was possible to control the system from the onshore substation. From there the system settings were reviewed. The wiper iteration was removed. This prevented the auto-run process which was constantly restarting the instruments after each wipe. A screen shot of the working system is included in Figure 32.
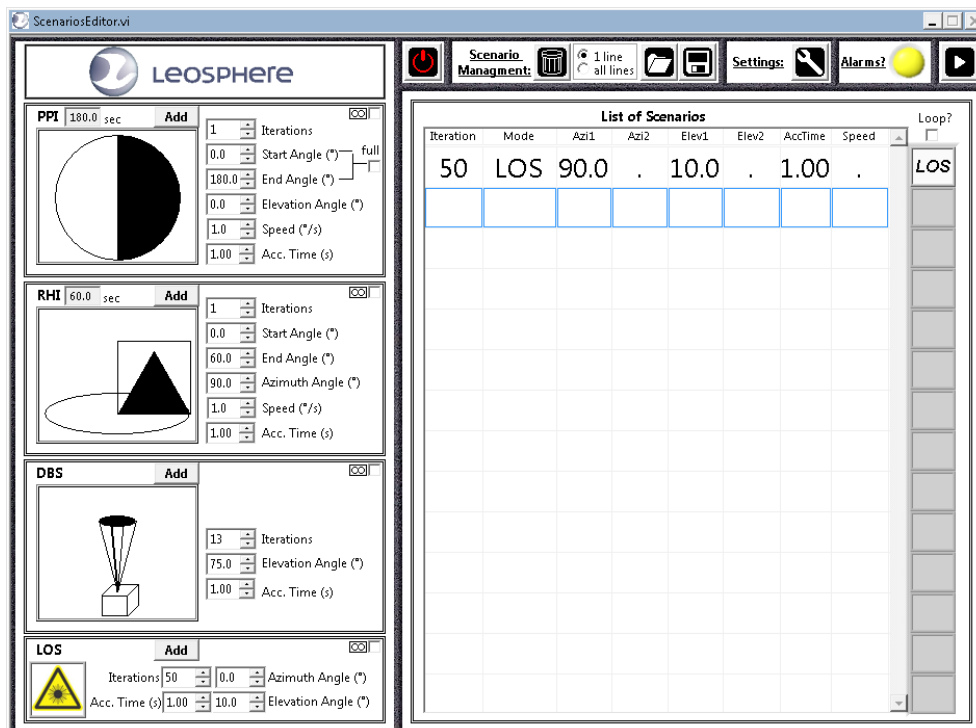
Figure 32: LIDAR Setting 3

It was established that this wiper error also effected the PTH status because once the wiper function was working correctly the PTH status was deemed "ok" by the system. A screen shot of the display is included in Figure 33.

Figure 33: LIDAR Setting 4

Following these corrections it is hoped that there will be no further issues with the LIDAR and a successful measurement campaign can be completed. When the campaign is completed it is intended to use the data to complete a reference comparison PPT.

8. Future Work

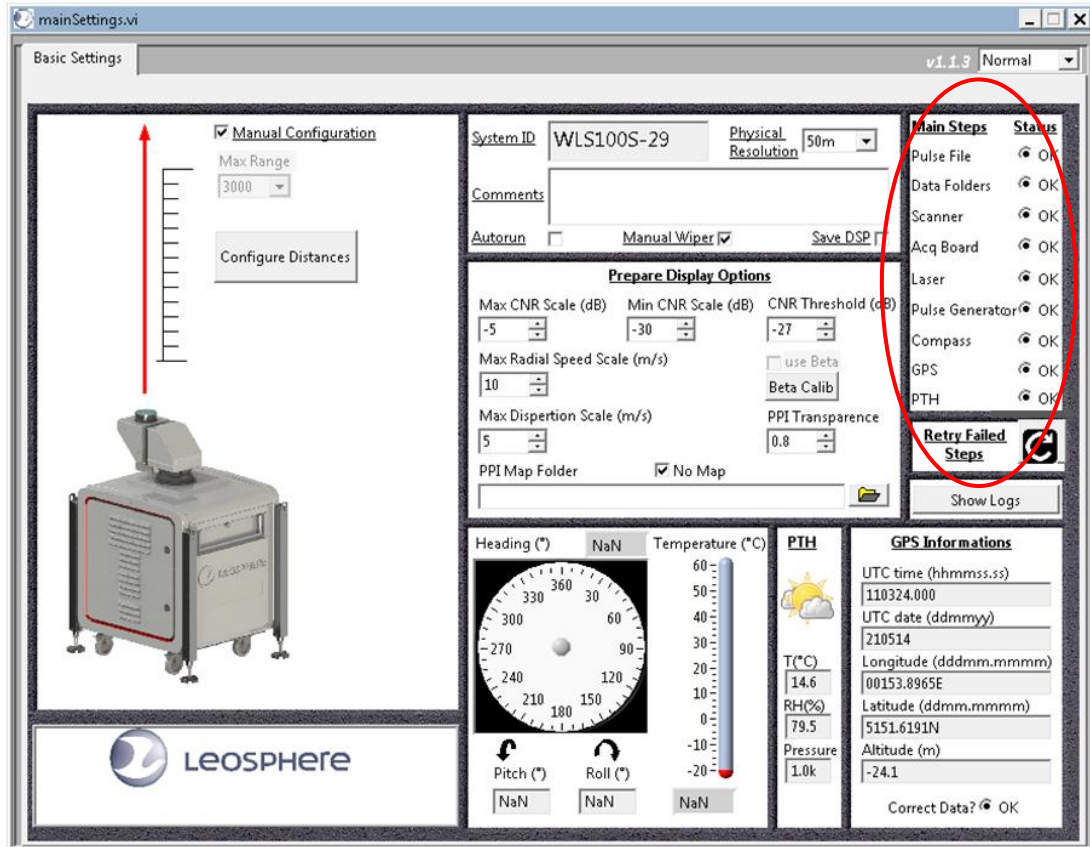This thesis has assessed the accuracy of LIDAR and confirmed the value of the PPT. In this section, work which would further validate this thesis and other potential cost savings which could be realised through the use of LIDAR are explored.

Further Validation

None of the following issues impacted the PPT results but it is expected that greater accuracy could be achieved if improvements in these areas are made.

- Calibration of the instruments used for the test could have been calibrated by an independent third party.

- Recorded data for a longer period would produce more accurate results. This analysis considers 4 months of recorded data only.

- This analysis was informal and cannot be used to negotiate with the wind turbine supplier even if it does show an underperformance. To successfully negotiate with the wind turbine supplier over underperformance a formal test performed by an independent third party should be performed to confirm the magnitude of underperformance.

- A similar PPT can be performed using adjacent wind turbines however the uncertainty will increase as the distance from the Met Mast will increase.

- A forward facing LIDAR measurement campaign should be conducted. This will improve the accuracy as the measurement will be done in front of the rotor instead of by the anemometer on the nacelle which is affected by the movement of the wind turbines rotor.

- The parasitic loads on the wind turbine should be measured to investigate whether these loads are having a greater influence than might normally be expected on the power curve.

It is proposed that in 2015 a forward facing LIDAR will be installed on wind turbine A and an independent PPT will be conducted. This will confirm the underperformance which this study found. If the shortfall of 3% is confirmed this will be used to negotiate lost revenue claims with the wind turbine supplier and a rectification to the route cause of why the wind turbines are underperforming. As resource assessment becomes more accurate these claims are becoming more and more common across the wind industry.

Similarly, these improvements could be made to the onshore measurement campaign which was conducted. This would also bring greater accuracy to that analysis too.

Future Use of LIDAR

Current wind turbines typically use nacelle mounted anemometers to measure wind speed. These instruments are well known to be subject to wake and turbulence due to the measurement of wind being taken behind the wind turbine blades.

Nacelle mounted forward facing LIDAR can measure wind conditions upwind. This measurement is unaffected by turbulence and wake effects due to the passage of the

wind turbine's own rotor blades. This provides a significantly more accurate way to measure wind conditions compared to nacelle mounted anemometry and wind vanes.

Wind turbine yaw control also depends on nacelle mounted measurement equipment which is vulnerable to inaccuracies. Improvements in this area could increase efficiency and also benefit the wind turbine's components through reduced loading. If a wind turbine's direction is slightly wrong then it will experience only a reduced component of the full wind speed. Eradication of the errors in this area can provide a significant revenue benefit to the wind farm developer.

While operational power curves can be measured using existing nacelle anemometry this is subject to the aforementioned errors meaning the accuracy associated with the performance of the wind turbine fleet is largely unknown. If forward facing nacelle mounted LIDAR provide more accurate wind speed measurement then the wind turbine operator will have an improved knowledge of whether operating wind turbines are performing in accordance with their performance warranty power curve.

The relative cost of a forward facing LIDAR in this case would obviously be in excess of the turbine anemometry and would be in the region of £100,000. This upfront capital costs though would be cancelled out by the benefits described above and it is expected that they would result in a pay back over the lifetime of a wind farm project. Operational and Maintenance costs would also be reduced through LIDAR alternatives. Met Masts require instrumentation replacement usually every two years. This can be costly as it requires special working at height specialists. This is not the

case for LIDAR because of its location on the ground although it will require a certain amount of inspection and maintenance on an annual basis but it is expected to be less than that associated with a Met Mast. In summary, it would be expected that the costs associated with the forward facing LIDAR would be less than those for the Met Mast.

9. Conclusions

The wind industry both on and offshore is growing and with it so does the size of wind turbines. We are now moving into an era where wind turbines in the region of 10 MW with rotor diameters of 200 meters will not be uncommon. Wind resource assessment is also keeping pace with the industry and the growing requirement for taller masts has led to the development of more flexible methods of measuring wind such as the emergence of remote sensing technologies.

LIDARs have been rigorously tested and as a result their accuracy has increased with improvements in areas such as signal processing and the cloud correction algorithms. Computation Fluid Dynamics (CFD) modelling is also becoming more common [20]. This too can reduce uncertainty associated with wind measurement and if used in association with LIDAR measurement can be employed to better understand areas which are difficult to measure such as complex and rough terrains.

The precision of LIDAR anemometry appears to have matured to a level where its use for stand-alone resource assessment is now an acceptable consideration for a wind farm. This thesis aimed to confirm LIDAR's accuracy and through the measurement

campaign conducted for this thesis an acceptable correlation between a LIDAR and Met Mast was achieved.

The PPT conducted has shown that wind farms can be significantly underperforming. LIDAR provide the developer with a cost effective method of performing this test and an effective way of measuring the wind farm's performance. Unfortunately due to time restraints, performing this test using LIDAR was outside the scope of this thesis. It is intended that the PPT can be reproduced using the scanning LIDAR installed in 2015.

It is clear that savings need to be made to reduce the cost of wind energy. It has been shown that LIDAR has huge potential here and with the technology improvements which have been seen in the last number of years it is clear LIDAR will continue to develop and it is likely to have a significant impact on both the accuracy of wind monitoring and the cost associated with it in the future.

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