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Wind farm performance

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Wind Energy
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MASTER THESIS

for

Student
Ali Marjan

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Wind farm performance

In order to develop the low-order tools needed to control individual wind turbines (WT) in a wind farm (WF) it is necessary to understand the key physics that need to be modelled and experimental data to calibrate and validate the model. For full-scale WFs there is a lack of experimental data, especially where all necessary parameters are controlled and measured. Therefore, one has to depend on model-scale experiments as benchmark cases (Krogstad et al., 2013, 2014; Pierella et al., 2014). The question of "scaling" of results from model scale to full scale needs to be addressed. Røkenes and Krogstad (2009) did a detailed and documented wind tunnel study of wind over a model terrain containing typical terrain formations of a WF. Such studies need to be extended with measurements both in model and full scale of the same WF. Scaling is also and important issue for control and optimizing performance for a single turbine. Model studies are well controlled, but there are significant uncertainties about scaling effects – e.g. Reynolds number effect on Lift, Drag and stalling characteristics for the airfoils used as rotor blades. Krogstad and Adaramola (2011) have investigated effects of pitching the blades and yawing the rotor w.r.t. incoming wind direction. The development of scaling methodologies requires that these types of investigations are performed at full scale such that they will be useful for the calibration of theoretical simulation models.

For the present study we have access to a 3-turbine wind farm with Vestas V27 turbines. The 3 WTs are located nearly on a straight line, thus enabling an evaluation of the performance of a turbine when it is exposed for an undisturbed wind, and when the turbine is located in the wake of an upwind turbine. The evaluation can be extended to address the "scaling problem" by comparison with the model scale studies cited above. For the measurement of wind characteristics there is deployed a Windcube v2 Lidar at the WF site, and equipment for data acquisition is to be installed in one WT to measure parameters for the WT performance.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

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X Field work

Department of Energy and Process Engineering, 02.06.2016

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Wind farm performance

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Abstract—**Performance of the wind turbine in the wind farm has been analyzed using IEC61400-12-1 wind turbine power measurement standard. Ten minutes averaged wind data was acquired from Windcube v2 LIDAR over the period of twelve months and compared with the 10 years' data of the weather station to do the wind resource analysis at the wind farm.**

This study estimates the efficiency of one of the wind turbines located in the wind farm by comparing the wind power potential at the wind farm with the actual power production of the wind turbine. Power curve of that wind turbine was also established by monitoring the output of the wind turbine with the help of a camera programmed to take pictures every minute. This data was averaged so that power curve is based on the ten minutes averaged data.

***Key words*-- Efficiency, LIDAR, Wind farm, Wind resource analysis, Power curve, Wind turbine**

I. INTRODUCTION

Environmental concerns and global demand of clean energy has increased the demand of renewable energy in general and wind energy in particular. The United States is thinking to expand their wind energy potential where 20% of all the energy need is provided by the wind energy. Norway has good wind energy potential due to its windy coast but not much is being availed compared to other European countries like Germany and Netherlands. [1] [2]

In order to increase the wind power projects in Norway, there is a need analyze the wind resource at a given site. The wind power density shows the wind energy potential of a given site and wind direction helps in positioning the wind turbines in the wind farm to increase the power production of the wind farm. LIDARs are extensively being used to for the accurate site analysis and performance testing of the wind turbines these days [3]. Moreover, the use of IEC61400-12-1 power performance measurement standard ensure consistency and accuracy in the measurement and analysis of the power performance of the wind farm. [4]

II. SITE DESCRIPTION

Ørland is located in Sør-Trøndelag county, Norway having the administrative centre in Brekstad city. It is located at the northern shore of Trondheimsfjord which further meets the Atlantic Ocean. Most of the terrain is normally flat, uniform and unique from the rest of Norway in the way that only 2% of the municipality exceeds the height of 160 m above the sea level. It consists of wide open spaces those are mainly used for agriculture and the main air base of Norway having coordinates (63.7045N, 9.6105E). There is also an official weather station of Meteorologisk institutt which is providing weather observation since 1957.

The wind farm being analyzed is around 2 Km away from the weather mast. It consists of three Vestas V-27 wind turbines. On the site there is a LIDAR (Light Detection and Ranging) having exact coordinates (63.70173N, 9.653E). The distance of LIDAR from the middle wind turbine is almost 112m and the direction is 18^0. The LIDAR is placed behind the hut as shown in figure 3.

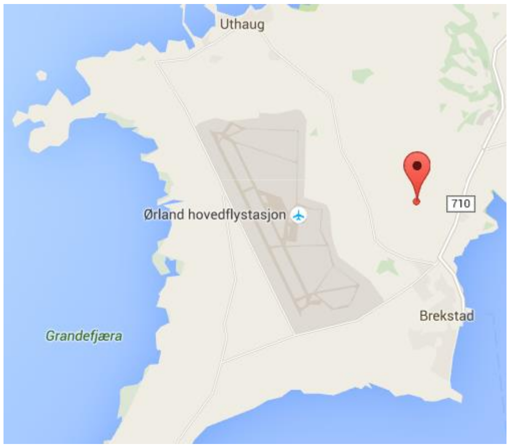

Figure 1: Map of area around wind farm

Figure 2: Top view of the wind farm

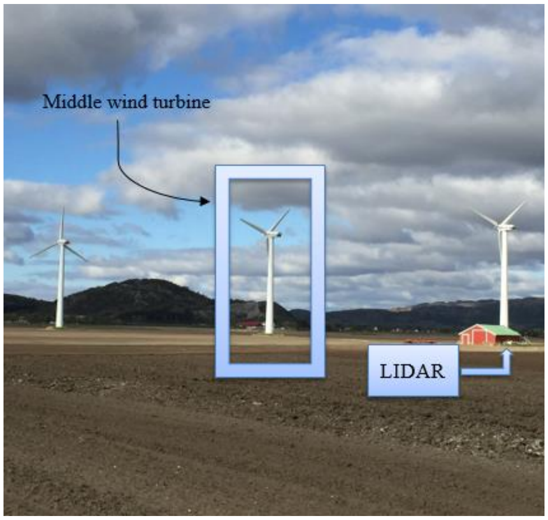

Figure 3: Wind farm under inspection

II. VESTAS V-27

The wind farm has three Vestas V-27 wind turbines. V-27 is upwind pitch regulated wind turbine with active yaw having rotor with three blades. The blades are made with glass fiber reinforced polyester each consisting of two blade shells and both are glued on the supporting beam. The power is transmitted to the generator by means of two stage gearbox. The generator is asynchronous and is connected to the grid. To achieve maximum performance at both low and high wind speeds the generator is changeable between 8 poles and 6 poles generators. Based on the generator-1 or generator-2, the rotor rotates at 2 rotational speeds.

Full feathering is used for the braking purpose and for the emergency stop hydraulic disk brakes are activated which is fitted with the high speed shaft of the gearbox. The variation in the blade position is performed by the same hydraulic system. The functions of the turbine are monitored and hence controlled by a control unit based on microprocessor. Yawing is achieved by the two yaw motors which are wheel mounted on the top of the turbine's tower.

The nacelle is fully closed in a glass fiber reinforced cover and it has access through central opening. Inside the nacelle there is an internal ladder for maintenance purposes. The specifications are given in detail in [5]. Few important specifications of V-27 are listed below.

Table 1: Vestas V-27 specifications

Rotor		**Airfoil**	
Diameter	27m	Air foil	NACA 63.214-63.235
Generator-1, rotational speed	43 RPM	Length	13 m
Generator-2, rotational speed	33 RPM	Width	1.3 m-0.5 m
Swept area	573 m^2	Twist	13^0
Diameter	27 m	**Tower**	
Number of blades	3	Height	30 m
Generator - 1		Diameter top	1.4 m
Rated power	225 kW	Diameter bottom	2.4 m
Rotational speed	1008 RPM	Hub height	31.5 m
Rated current	396 A	**Operational data**	
Generator - 2		Cut-in speed	3.5 m/s
Rated power	50 kW	Rated wind speed	14 m/s
Rotational speed	760 RPM	Cut out wind speed	25 m/s
Rated current	101 A	Rated power	225 kW

A. Airfoil

The Airfoil for HAWTs are often designed to be used at low angle of attacks, where lift coefficients are fairly high and drag is low. Many different standard airfoils developed for aircraft have been used on the HAWTs. The *NACA 230XX series*, *NACA 63-2XX series* and *NACA 44XX series* airfoils have been used on many modern HAWT units. [3]

The airfoil used for the Vestas V-27 as given in [5] is NACA 63214-63235. For this report NACA 63218 is used to analyse the airfoil data. The airfoil data was obtained with the help of "Design foil" software.

Figure 4 shows the relation between AoA and lift coefficient for NACA-63218 airfoil. The value of lift at zero AoA (Cl_0) is 0.188. While the stall angle of attack is 14.2^0.

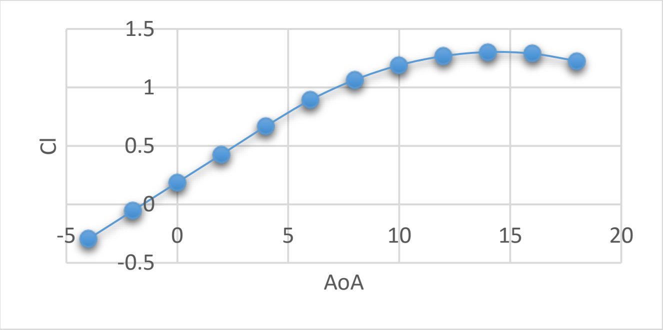

Figure 4: Cl vs AOA

Figure 5 shows the variation of lift to drag ratio with the lift coefficient and it is very important graph to obtain the design parameters of the rotor. The maximum L/D value is 83.6 for NACA-63218. This graph is used to find design lift coefficient which is the lift coefficient at which L/D is maximum. It is done so that maximum power can be extracted from the wind. Design lift coefficient of the airfoil is 0.67 while the maximum value of L/D is 83.6.

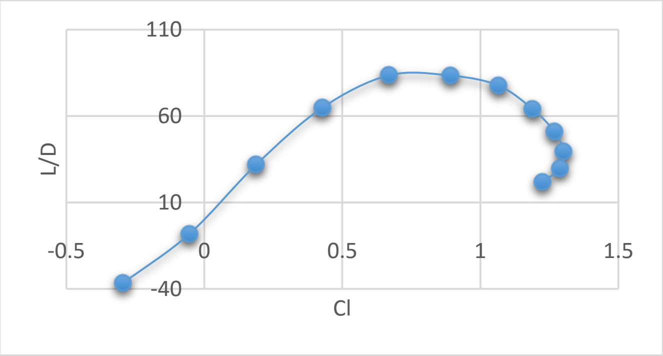

Figure 5: Cl vs L/D

B. *Pitch control mechanism*

In a variable speed wind turbine, the rotor speed of the wind turbine continuously varies and matches the current wind speed. In a fixed speed configuration, as the wind speed crosses the cut-in speed the brakes of wind turbine are released and it starts rotating at a fixed wind speed up to its rated power. As the rated power of the wind turbine is reached, power production is then regulated with the help of either pitch regulation or stall control. [3]

The V-27 rotates at only two wind speeds. For lower wind speeds it rotates at 33 RPM and for higher wind speed rotation speed of the rotor is 43 RPM. For that reason, the V-27 uses pitch control mechanism to regulate its power. With the pitch regulated mechanism, varying amounts of power can be extracted by changing the pitch angle of the wind turbines. As the wind speed increases, the blades rotate about a pivot hence decreasing the angle of attack. The blades are brought back to its position as the wind speed decreases. This method of varying pitch angle is used so that optimum power can be obtained at all the wind speeds.

C. *Power curve*

The Power curve shows the turbine's net power output versus the wind speed. Power output data provided in [5] versus given wind speeds at standard air density is shown in the figure 6. V-27 reaches its rated power at the wind speed of 14 m/s.

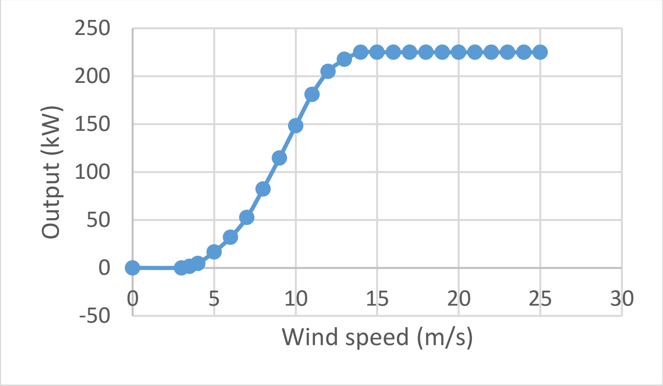

Figure 6: Power curve

III. WIND RESOURCE ANALYSIS

A. *Theory*

A wind resource analysis is the most important step for measuring the wind power potential of any site. There are number of ways to model the wind speed over the period of time using the probability density function. Weibull and Rayleigh distributions are the most commonly used in wind data analysis. Rayleigh distribution is based on just mean wind speed while Weibull distribution is based on two parameters and hence is more powerful, versatile and useful. In this study Weibull method is used for the analysis due to the better approximation it gives with 2 parameters. The detailed discussion about the Weibull distribution is given in [6]. The general form of Weibull distribution function is

$$\boldsymbol{f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^{k}}} \tag{1}$$

Where $f(u)$ is probability of observing the wind speed u, k and c are scale and shape factor respectively. There are several methods of calculating the Weibull k and c factors but maximum likelihood method is used in this analysis. This method uses the following equation for the iterative process to calculate k.

$$\boldsymbol{k = \left[\frac{\sum_i^N U_i^k \ln(U_i)}{\sum_i^N U_i^k} - \frac{\sum_i^N U_i}{N}\right]^{-1}} \tag{2}$$

By using above value of k, one can find the value of scale factor c.

$$\boldsymbol{c = \left[\frac{\sum_i^N U_i^k}{N}\right]^{1/k}} \tag{3}$$

B. *Results*

The wind data is extracted from the Windcube v2. Windcube v2 collects the measurements at different heights till 200 m. Hub height of the Vestas V-27 is 31.5 m, hence the wind data is extrapolated at 31.5 m for the analysis.

1) *Wind speed frequency*

Figure 7 shows the frequency distribution of the wind speed at the hub height of 31.5 m with bin size of 0.5 m/s. The wind site being analyzed has Weibull parameters k = 1.84 and c = 7.46 m/s. Lower value of k shows that the wind speed is not steady and varies to different range of values. Value of c shows that the average wind speed at the site is 7.46 m/s.

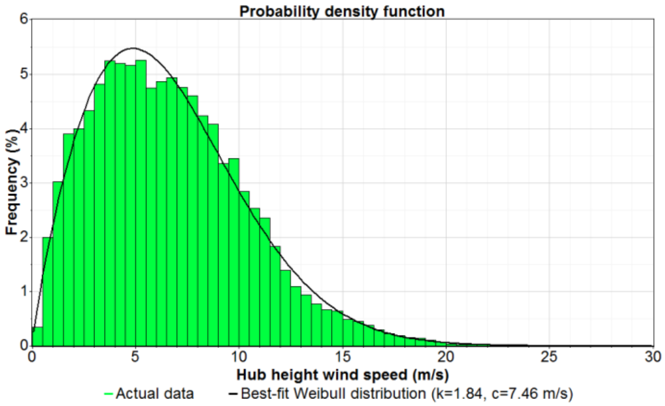

Figure 7: Wind speed frequency

2) *Wind direction*

Wind rose is a graphic tool that helps in understanding the wind direction at the given site. It shows the frequency with which the wind direction can fall in a certain direction sector. Figure 8 shows the percentage frequency with which the wind blows from a certain sector. Most of the wind comes from the south-east direction (40%) while approximately 21% of the wind comes from south-west direction. The contribution of the wind coming from the north is quite less and does not contribute much in the power production. Position of the wind turbines are shown with the blue line. Wind turbines are in straight line and makes 173^0 angle from the north. It can be noticed that middle wind turbine is in the wake of other wind turbines approximately 13% of the total time.

Figure 9 shows the detailed analysis with the method of bins speed from each direction sector. Bin size of 6 m/s is used with the sector length of 30^0. It can be seen that slower wind speed (0-6 m/s) comes from all the directions and medium wind (6-12 m/s) as shown with the green color blows from the south and west directions. While the major portion of the strong wind (12-24 m/s) shown with yellow and orange color in the figure, blows from the south-east and south-west direction throughout the year.

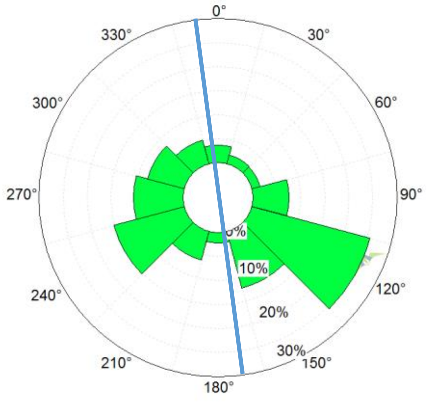

Figure 8: Frequency wind rose

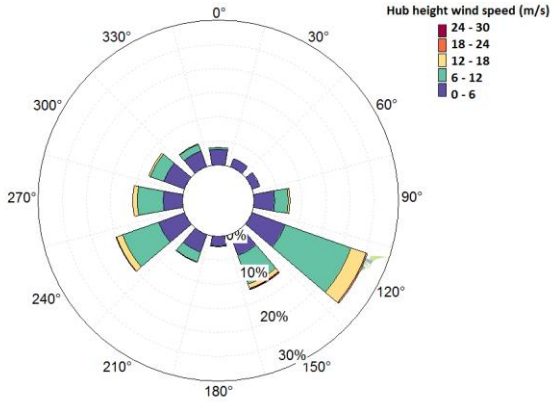

Figure 9: Wind rose with method of bins

3) *Daily variation of wind speed*

Figure 10 shows the variation of wind speed through the day for the whole year. The average variation in the wind speed is not too high through the year but the wind speed is slightly higher in the day time as compared to the night time. The maximum average wind speed occurs at around 9 a.m. and then it declines and reaches its minimum at around 8 p.m.

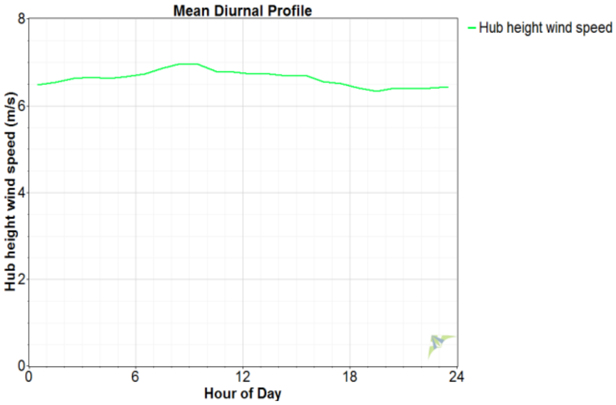

Figure 10: Mean diurnal profile

4) *Mean monthly wind speed*

The wind data extracted from the Windcube v2 includes the wind speed data. Based on 10 minutes averaged data, average wind speeds in each month is obtained. It can be seen from figure 11 that wind is stronger in the winter months and the average wind speed reaches its maximum in December (9.70 m/s). Summer months have lower wind speed and hence produces lower output with minimum value in July is 4.27 m/s. The wind speed starts increasing after July and decreases after reaching its peak in December. Due to lower wind speeds in the summer months, lower power production is obtained by the wind farm from March till September.

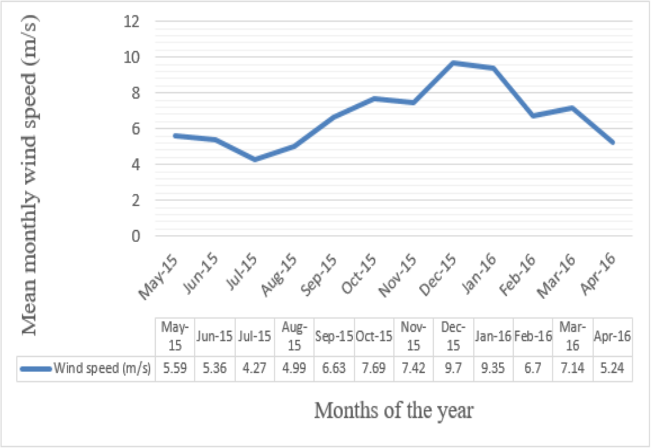

Figure 11: Mean monthly wind speed (m/s)

5) *Vertical wind shear profile*

The vertical wind shear profile is used to show how the wind speed at a given site varies vertically at different heights. According to the boundary layer theory, the wind speed increases as the height above the ground increases. Mean vertical wind shear profile of the wind farm for 12 months is shown in the figure 12. It can be seen that wind speed is varying exponentially with height. Because of this reason tall wind turbines can harness more power out of the wind.

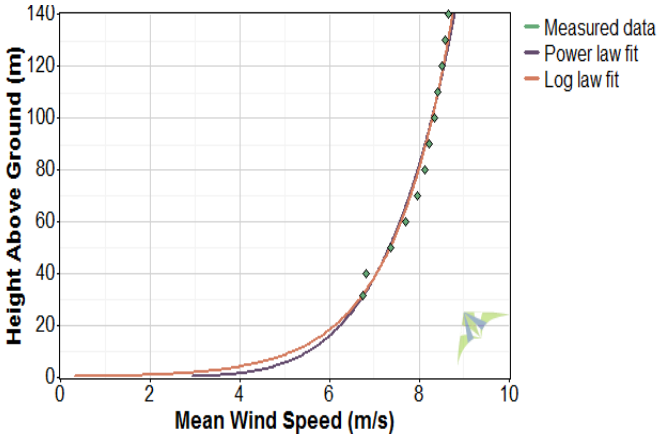

Figure 12: Vertical wind shear profile

6) *Wind power class*

The wind power class is a number that indicates the energy content at a given site. It is based on the mean wind power density at 50 m above the ground according to the table 2. Usually class 3 or above are treated as suitable for wind power production.

Table 2: Wind power class

Wind Power Class	Description	Power Density at 50m (W/m^2)
1	Poor	0-200
2	Marginal	200-300
3	Fair	300-400
4	Good	400-500
5	Excellent	500-600
6	Outstanding	600-800
7	Superb	800-2000

The monthly wind power density and wind power class of the wind farm under observation is shown in the table 3. It can be seen that wind farm has good prospect for the wind power production except in the months of April, June and July where wind power class is less than 3. However other months show good prospect for the power production. Wind power class of 7 is obtained in December and January which is rated in 'superb' category.

The wind speed at a given site varies in the vertical direction so the WPD at each height above the ground can be calculated. The linear least squares regression is used to find the straight line that best fits the natural logarithmic variation of mean wind speed with natural logarithmic variation of height. To find the best estimate of wind power density of whole year at a given site, windographer calculates the value of mean power density at which the line of best fit crosses 50 m height. It can be noticed from figure 12 that mean WPD at 50m is 479 W/m^2 which is wind power class 4 and this site is described as 'good' for wind power production.

Table 3: Monthly wind power class

Month	Mean wind speed (m/s)	Power Density at 50m (W/m^2)	Wind power class
Jun-15	5.36	257.5	2
Jul-15	4.27	126.2	1
Aug-15	4.99	225	2
Sep-15	6.63	442	4
Oct-15	7.69	622.3	6
Nov-15	7.42	577.4	5
Dec-15	9.7	1147.6	7
Jan-16	9.35	1004.6	7
Feb-16	6.7	429.5	4
Mar-16	7.14	453.5	4
Apr-16	5.24	269.6	2

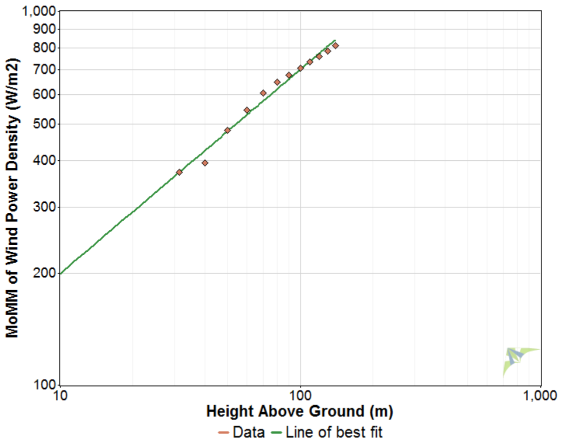

Figure 13: Mean of monthly means of WPD vs height

C. Comparison of on site data with met station data

So far the wind data analysis of 12 months' period is shown but in order to get long term analysis of the wind farm there is a need to compare it with the met station data. Measure Correlate Predict (MCP) method is used to analyze the relationship between the wind data of the target site and the nearby reference station (met station). With the help of statistical process based on this relationship, long term target site data is predicted. [7]

Target data of 12 months was compared with the 10 years' data from the met station with 7.9 months of concurrent period. Figure 14 shows that the correlation is not that good but it is evident that both data sets are from the same area. This provides the basis to predict the long term data of the wind site based on reference data and it is shown in figure 15. The target data complements the long term predicted wind speed quite well. It can be concluded that winter months are windier than the summer months while December and January being the windiest months. The wind direction based on 10 years' data shows that most of the wind comes from south-east and south-west direction (figure 16).

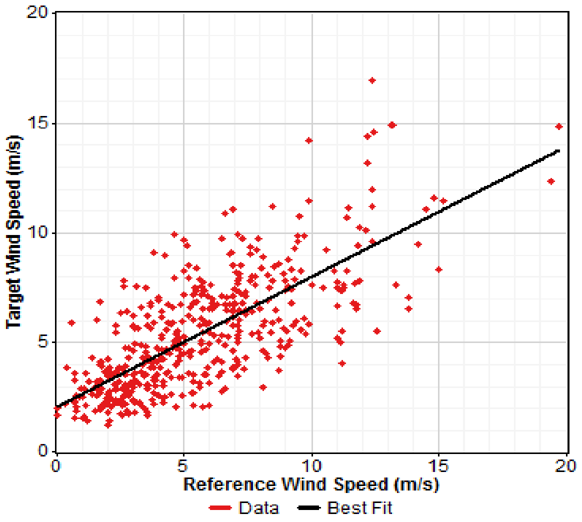

Figure 14: Correlation between target and reference wind speeds

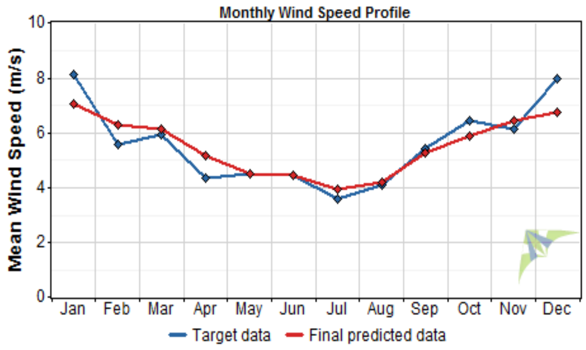

Figure 15: Long term monthly predicted wind speed

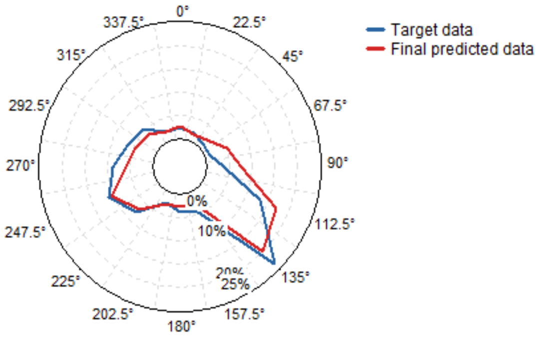

Figure 16: long term predicted wind direction

IV. POWER PERFORMANCE

A. Theory

The power available in the wind was calculated by the 'method of bins' based on the IEC61400-12-1 standard. The purpose of this standard is to give uniform methodology for the measurement, analysis and reporting of power performance testing of the wind turbines.

The theoretical maximum efficiency known as Betz limit is 59% and no wind turbine can cross this figure. But for real wind turbines this figure is even lower and usually it is 30-45% even for the best designed wind turbines when the losses due to gearbox, generator, bearings and wake effect losses are considered [6]. Power available in the wind is given by:

$$\boldsymbol{P_{avail} = \frac{1}{2}\rho A V^3 C_p} \tag{4}$$

Where V is velocity, A is swept area, ρ is the standard air density, C_P is the power coefficient and P_{avail} is the power available in the wind. The power data is obtained by applying "method of bins" using 0.5 m/s bins and by calculating the mean values of normalized wind speed and power output in each bin.

$$\boldsymbol{V_i = \frac{1}{N_i}\sum_{j-1}^{N_i} V_{n.i.j}} \tag{5}$$

$$\boldsymbol{P_i = \frac{1}{N_i}\sum_{j-1}^{N_i} P_{n.i.j}} \tag{6}$$

$$C_{P,i} = \frac{P_i}{\frac{1}{2}\rho A V_i^3} \qquad (7)$$

Where,

V_i	is the normalized/averaged wind speed in bin i
$V_{n.i.j}$	is the normalized wind speed of data set j in bin i
P_i	is the normalized/averaged power output in bin i
$P_{n.i.j}$	is the normalized power output of data set j in bin i
N_i	is the number of 10-minute data sets in bin i
$C_{P,i}$	is the power coefficient in each bin

B. Methodology

The wind data from the Leosphere Windcube v2 was obtained for 11 months and power available in the wind was calculated with the help of Windographer (wind analysis software). While the actual monthly power produced by the middle wind turbine was noticed for the same period (11 months). The actual power produced when compared with the power available in the wind gave efficiency of that middle wind turbine. It would have been ideal if the power data of other two wind turbines was available but the other two wind turbines did not have power production data for the same period. Eventually the focus was set on the middle wind turbine and all the results and comparisons given in this report are based on middle wind turbine.

Actual C_P curve of the middle turbine was obtained by placing a camera in front of the output display of middle wind turbine. The camera was programmed to take one picture every minute and then the 10 minutes averaged data was obtained and plotted according to the instructions given in [4].

C. Results

1) Mean power and energy output

Mean power and energy output data of 11 months is tabulated below. Gross mean power and energy data is based on the power available in the wind that V-27 should ideally harness based on the power curve data given by the manufacturer. However, the actual mean power and energy data indicates the actual power and energy production of Vestas V-27 at the wind farm.

Table 4: Mean power and energy output data

Month	**Mean wind speed (m/s)**	**Gross mean power (kW)**	**Actual mean power (kW)**	**Gross mean energy (kWh)**	**Actual mean energy (kWh)**
Jun-15	5.36	42.8	38.15	30816	27470
Jul-15	4.27	22.3	17.92	16591.2	13334
Aug-15	4.99	37.7	26.625	28048.8	19809
Sep-15	6.63	67.3	46.96	48456	33814
Oct-15	7.69	83.8	70.16	62347.2	52204
Nov-15	7.42	82.2	65.12	59184	46887
Dec-15	9.7	122.3	101.01	90991.2	75153
Jan-16	9.35	121.1	100.24	90098.4	74578
Feb-16	6.7	68.1	59.46	47397.6	41388
Mar-16	7.14	74.7	65.79	55576.8	48950
Apr-16	5.24	38.4	34.38	27648	24756

The monthly variation of the mean power output is shown in the figure 12. It can be seen that power production is more in the winter months due to the higher average wind speed. Maximum power output is obtained in December and January where actual power production of the middle wind turbine in the wind farm is 101.01 kW and 100.24 kW respectively. Proportion of the wind energy in these two months is 30% of the annual power production. However, summer months are not that good with power production perspective and lowest power production is 17.92 kW in the month of July (2.9%). Other noticeable thing in the figure 17 is that performance of middle wind turbine varies, mostly the losses are between 10-20% except in the months of August and September where the wind turbine was not operational due to the maintenance reasons.

Figure 18 depicts the actual mean energy produced by V-27 and the net mean energy roughly estimated by the windographer considering 16% overall losses. These losses are combination of the wake effect, generator losses, availability losses and bearing losses. The curve is a close fit except in August and September where the availability losses are quite high due to the maintenance work.

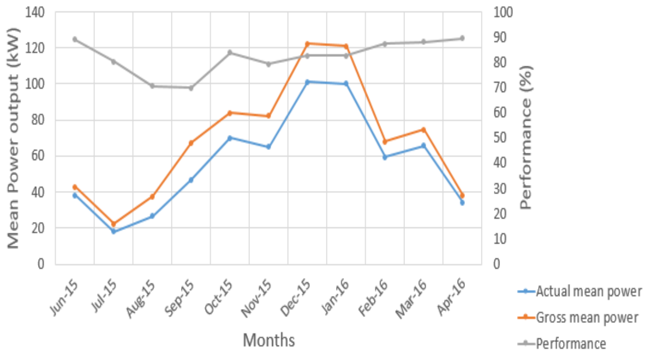

Figure 17: Mean power output

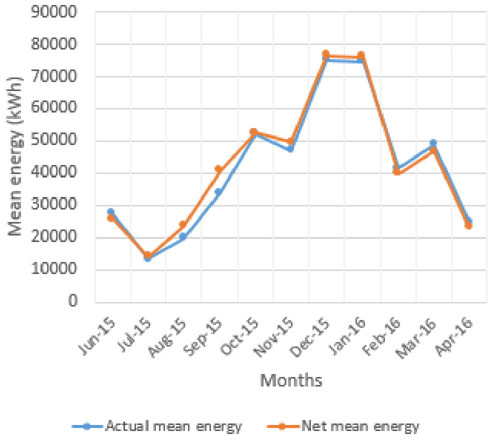

Figure 18: Actual and net monthly energy output

2) Histogram of gross power

The histogram of the gross power is obtained based on the wind speed measured by LIDAR. It shows the frequency of distribution of the gross power produced by the wind turbine at the wind farm. The wind turbine produces less than 5 kW power 28% of the time and 4% of the time it produces its rated maximum power (225 kW).

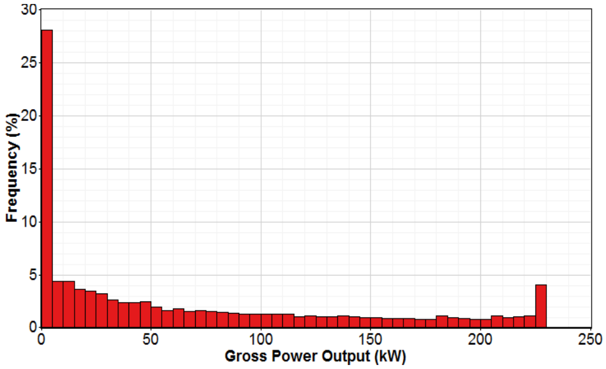

Figure 19: Histogram of gross power

3) Power curve

The performance of a wind turbine is widely characterized by its power curve. Power curve of V-27 is shown in the figure 20. The nacelle wind speed and power data was used to obtain the scatter plot. The best fit curve of the 8th order was plotted in MATLAB and it shows good fit with the data. Higher order best fit curve was used because of lesser data points of higher wind speeds for getting better fit to the data points.

However, figure 21 shows the actual power curve of the V-27 at the wind farm obtained with best fit curve and the power curve given by the manufacturer. It can be observed that the power curve of the wind turbine at the wind farm matches almost exactly with the manufacturer's power curve till the wind speed of 7 m/s. However, this gap widens and is maximum (almost 16%) at 11.80 m/s. It is not only because of losses but also due to the unavailability of data points above the wind speed of 10.5 m/s.

The wake effect of other wind turbines is also one of the loss factor. It is evident from the wind direction data that middle wind turbine is under the wake effect of other two wind turbines almost 14% of its total operational time in 12 months. The first wind turbine from the south direction is in the wake 6% and the third wind turbine is also estimated to be in the wake 14% of its operational time. From this it can be said that first wind turbine contributes most to the total electrical power production of the wind farm.

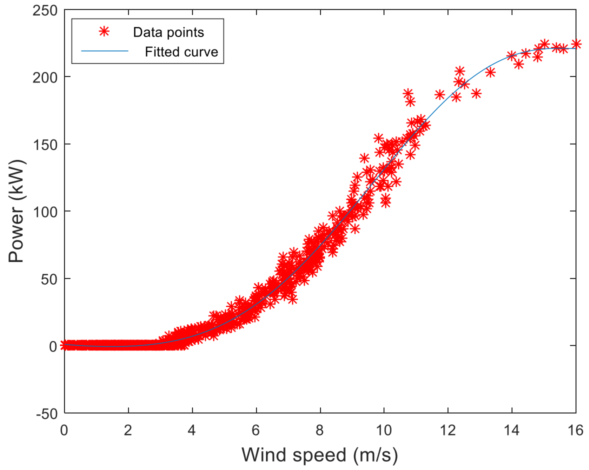

Figure 20: Power curve with scatter plot

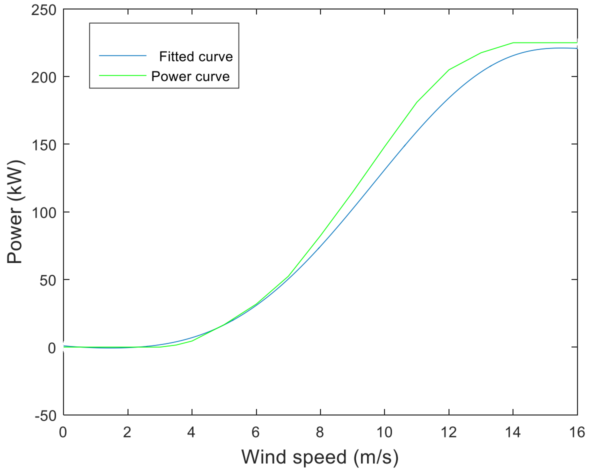

Figure 21: Comparison of two power curves

4) Efficiency

Power coefficient is the measure of the efficiency of the wind turbine. Cp is defined as the ratio of actual power produced by the wind turbine to the power available in the wind. The data used to obtain the power curve was further used to obtain power coefficient at each wind speed and eventually Cp curve as a function of wind speed was obtained as shown in figure 22. The plot has lot of scatter and few points are crossing the Betz limit, it is because nacelle wind power varies suddenly with the wind speed and the data obtained does not represent the precise efficiency of the wind turbine. The polynomial used to obtain the best fit curve is of 4th order.

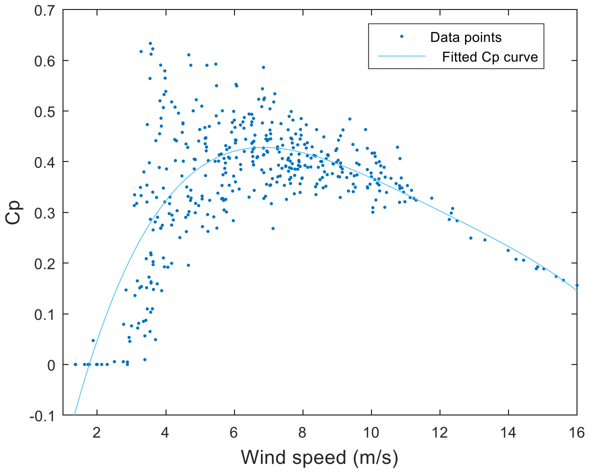

Figure 22: Efficiency curve

V. CONCLUSION

The wind resource analysis on a wind farm consisting of 3 wind turbines was performed and the data of 12 months was obtained from the LIDAR positioned at the wind farm. For long term analysis, ‘Measure Correlate Predict’ method was used to predict wind behavior by comparing it with the 10 years’ wind data obtained from the weather station located around 2 km from the wind farm. It was observed that winter month contributed a lot more towards annual power production where only December and January contribute 30% of the annual power production. Moreover, mostly wind comes from south-east and south-west direction at the wind farm. Wind power class of the wind farm was 4 and close to 5 which is rated as good to excellent.

Mean monthly power and energy output of one wind turbine was obtained with and without losses for V-27 and were further compared with actual power production of the wind turbine. Actual power production was lower than the power production calculated based on the power curve given by the manufacturer because of almost 16% losses due to the wake effect, generator losses, availability losses and bearing losses. The power curve obtained by the best fit curve of the observed data of the wind turbine in the wind farm showed similar trend as the actual power curve. However, power coefficient obtained by observing power at each minute showed some scatter because of the crude method used and less number of observations. Further work should be performed by installing a data logger so that accurate time series of the wind turbine can be obtained which will improve the accuracy of power curve and power coefficient curve. Power output data of other two wind turbines should be monitored so that the effect of wake on each wind turbine and the whole wind farm can be observed.

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