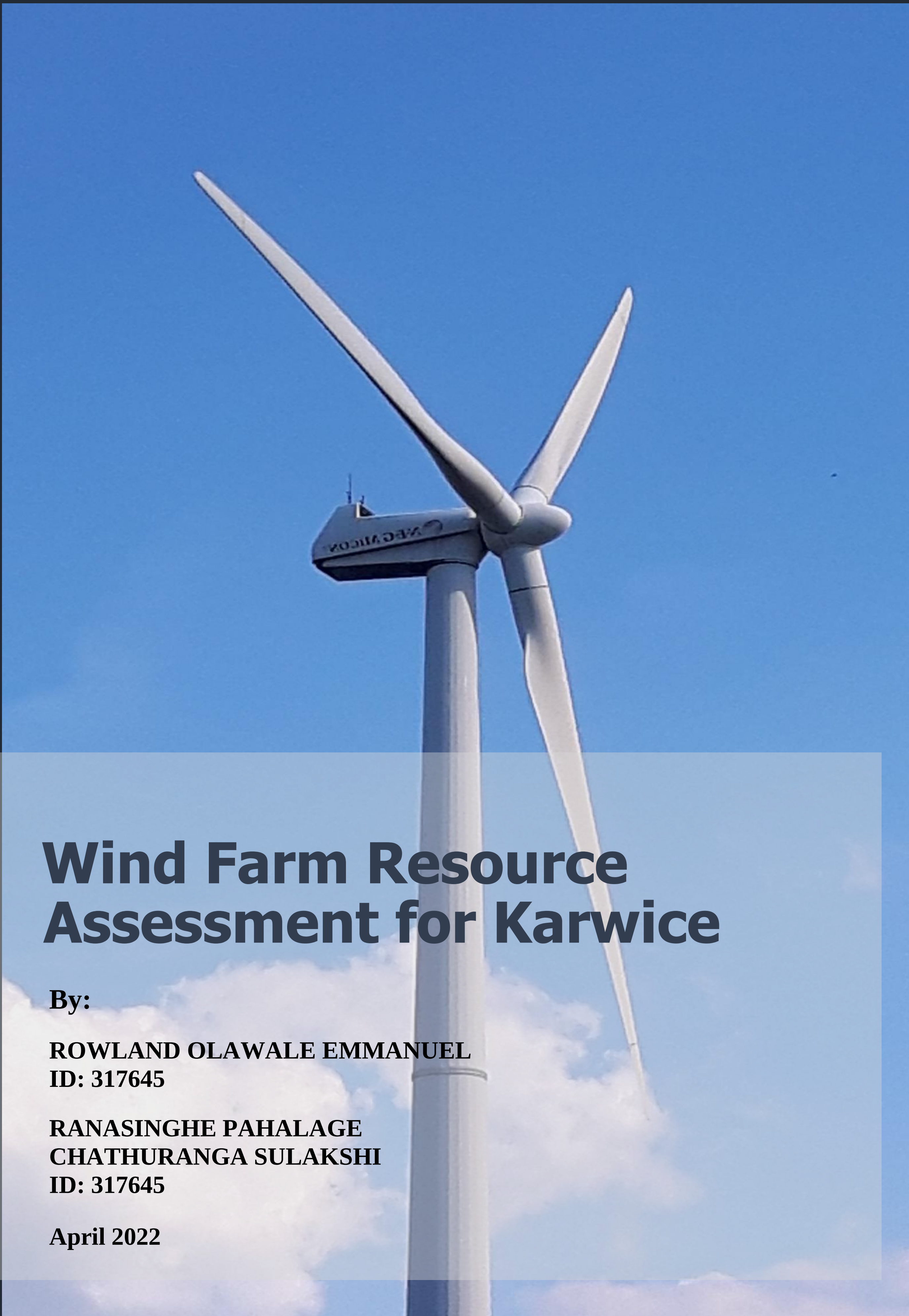

Wind Farm Resource Assessment for Karwice

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Abstract

Wind resource is the amount of energy that can be generated from a wind power plant over its period of existence. As such, this analysis assessed the wind resource of Karwice using metrological stations in Lebork and Koszalin as the basis for the assessments. Prior the determination of the stations to be analysed, a comprehensive examination of the various meteorological stations adjourning Karwice were examined to determine the station whose characteristic intimately align with Karwice. Consequently, Lebork and Koszalin were selected and analysed using R version 3.6.3 programming software.

The analysis was carried out on the two stations and presented in form of a book section. Lebork's analysis revealed that for Vestas' wind turbine, the total wind energy generated is 3827 [MWh/a] and 4443 [MWh/a] for 80m and 105m respectively. For Nordex, the total wind energy generated is 4384 [MWh/a] and 4931 [MWh/a] for 80m and 100m respectively. Meanwhile, for Nordex turbine in Koszalin the total energy generated is 3720 [MWh/a] and 4227 [MWh/a] at 80m and 100m respectively. While the total energy generated for Vestas is 3239 [MWh/a] and 3795 [MWh/a] for 80m and 105m respectively. For Lebork and Koszalin, the Nordex_N100_2.5MW wind turbine seems to be more efficient and better suited for the site than Vestas_v90_3MW.

Findings from the analysis revealed that wind speed are stronger in winter months than the summer months, and as well as in daytime than nighttime. Wind speed greatly influenced the amount of power and energy generated from the wind turbines. A very low wind speed generates a completely small or zero energy. While higher wind speeds generated much higher energy. Similarly, hub heights also influence the power and the amount of energy generated. The higher the hub height, the more the energy likely to be generated, and the lower the hub height the lower the energy likely to be generated. Hence, adequate consideration should be given to these factors including the direction of wind in wind resource analysis as it greatly helps to reveal the sector with the most abundant and as well as the strongest winds which are all necessary in planning the installation and the siting of a wind turbine or a wind farm.

Contents

1.0 Introduction

Wind resource is basically defined as the amount of energy that can be generated from a wind power plant over its period of existence. Implicitly, wind resource assessment involves estimating the amount of wind-driven energy that can be generated from a wind power plant over the course of its useful life. Another variety of definition describes the assessment as the process by which wind power developers estimate the future energy production of a wind farm (Energy Sector Management Assistance Program, 2022).

Wind resource assessments are crucial to the successful development of wind farms, and overestimation or underestimation could bring about serve consequences in the operation of the farm. In line with this backdrop, this project seeks to carefully assess the wind resource likely to be generated in a wind farm sited at Karwice town in pomorskie voivodeship using meteorological data from koszalin and lebork that are withim 100km of Karwice.

1.1 The Study Area – Wind Farm Localisation: Karwice

As shown in Figure 1a, the wind farm is hypothetically proposed to be sited at Karwice which is a village in the administrative district of West Pomeranian Voivodeship, located in north-western Poland (Central Statistics Office (CSO), 2022). Karwice lies in latitude 54° 19' 50.5" and longitude 16° 33' 44.8". The village is located at about 165 km from the regional capital Szczecin. It has a population of 410 inhabitants (CSO, 2022). The climate of Karwice follows closely with that of Szczecin, hugely influenced by the sea breeze with partly cloudy summers and long, very cold, snowy, windy, and cloudy winter seasons. Over the course of the year, the temperature typically varies from 27°F to 74°F and is rarely below 12°F or above 84°F (Weather Spark, 2022). Wet days in the study area varies throughout the year. The wetter season lasts 8.1 months, from May 13 to January 15, with more than 24% chance a day being wet. The month with the most wet days in the study area is June, with an average of 8.5 days with at least 0.04 inches of precipitation (Weather Spark, 2022). Rain falls throughout the year in Karwice with the highest volumes occurring around July of every year.

After thorough considerations of the characteristics of the meteorological stations close to Karwice, a decision was finally made to select meteorological stations is Koszalin and Lebork for the estimation of the wind energy resources of the farm to be located at Karwice. The details of the criteria for selection is provided in Section 2.0.

Figure 1a: The satellite Imagery of the Meteo Sites Considered with Respect to Karwice

Source: *(Google Earth, 2022)*

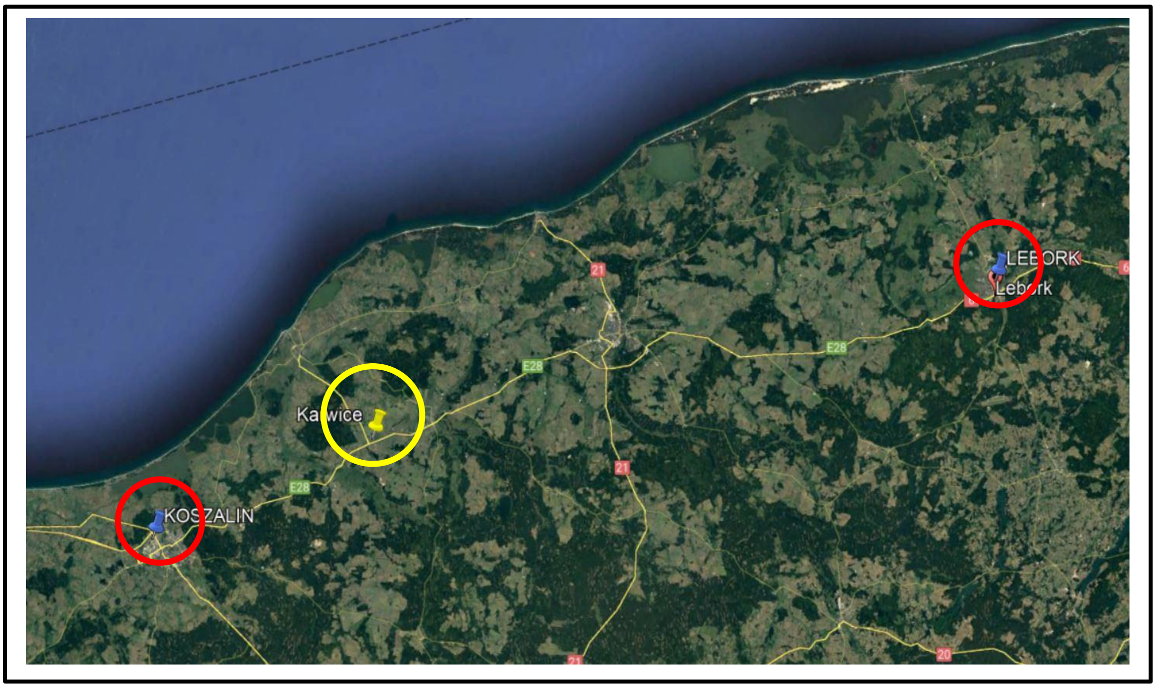


Figure 1b: The satellite Imagery of the Study Area, in relation to the two sites analysed

Source: *(Google Earth, 2022)*

2.0 Materials and Methods

This study started with identifying the location of the proposed wind farm (that is Karwice) using google earth imagery. After establishing its location, some of the various meteorological stations shown in Figure 1a were examined to assess the stations whose characteristics intimately aligns with the characteristics of Karwice. As shown in Table 1, and Figures 1a and 1b the result revealed that the characteristics of Koszalin and Lebork closely corresponds with the characteristics of Karwice. Therefore, the two stations were used to estimate the wind resource of the farm to be sited in Karwice. To achieve this, the time series of the meteorological parameters (wind speed, wind direction, temperature, pressure etc.) of the two meteorological stations that met the criteria were extracted from the course repository and were consequently analysed using R software version 4.1.2. Specifically, processes that were followed includes.

1. Identification of Karwice using GoogleEarth
2. Identification of meteorological stations close to Karwice
3. Determination of two meteorological stations (i.e. within 100 km radius) whose characteristics intimately align with that of Karwice
4. Acquiring time series (with 1-hourly time resolution) for meteorological parameters (wind speed, wind direction, pressure, temperature) for Koszalin and Lebork for the year 2014.
5. Analysing the data using R software with the aid of "bReeze" library
6. Presentation and interpretation of wind data with corresponding estimation of potential power and energy production of wind turbines to be sited at Lebork and Koszalin meteorological stations.

2.1 Selection of Meteorological Station

Prior selection of station, a comprehensive analysis of some meteorological stations close to Karwice was carried out to select two stations whose characteristics closely match that of Karwice. As depicted in Table 1 and Figures 2 – Figure 7, the results of the analysis revealed that Lebork and Koszalin are the two stations whose characteristics match that of karwice. As such, the wind data for the two stations were analysed, and used to estimate the power and energy potential of wind turbines to be sited at the stations.

Table1: Summary of the Meteorological Stations in investigated with respect to Karwice

Station/Localisation	Avg. Wind Speed (m/s) 10m	Avg. Wind Speed (m/s) 100m	Distance to Karwice (km)	Elevation Above SL (m)
Karwice	**5.04**	**7.46**	**-**	**43**
Koszalin	**5.57**	**7.12**	**30.4**	**39**
Lebork	**5.16**	**7.06**	**77.8**	**28**
Kolobrzeg	**6.27**	**8.06**	**66**	**11**
Darlowek	**5.99**	**7.88**	**13**	**6**

Source: Sulakshi & Rowland's Work, 2022

A) Karwice

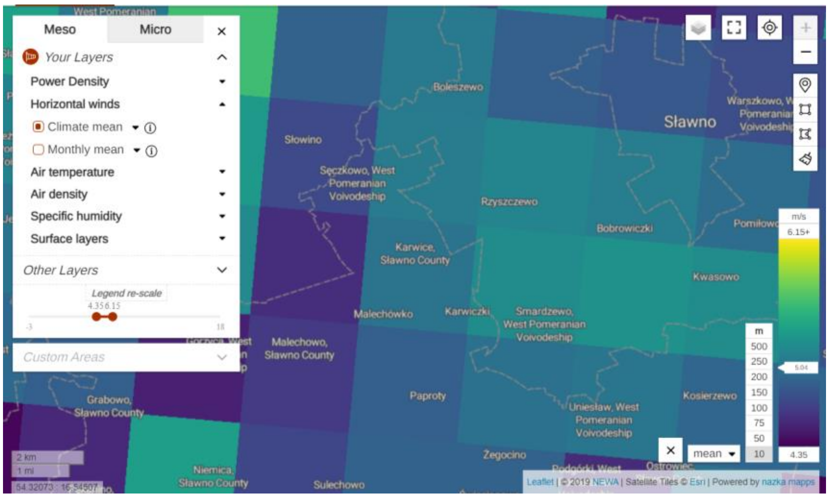


*Figure 2a: Wind speed of **Karwice** at 10m – Meso Scale (Average windspeed = 5.04m/s)*

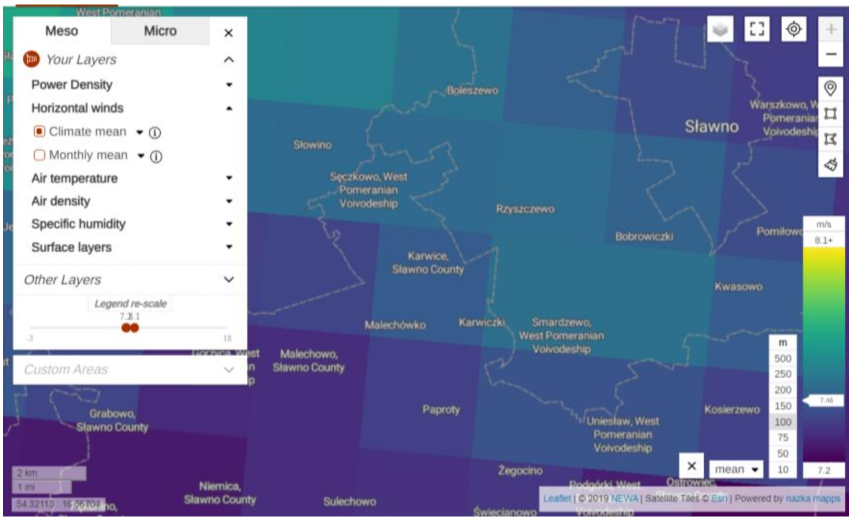


*Figure 2b: Wind speed of **Karwice** at 100m – Meso Scale (Average windspeed = 7.46m/s)*

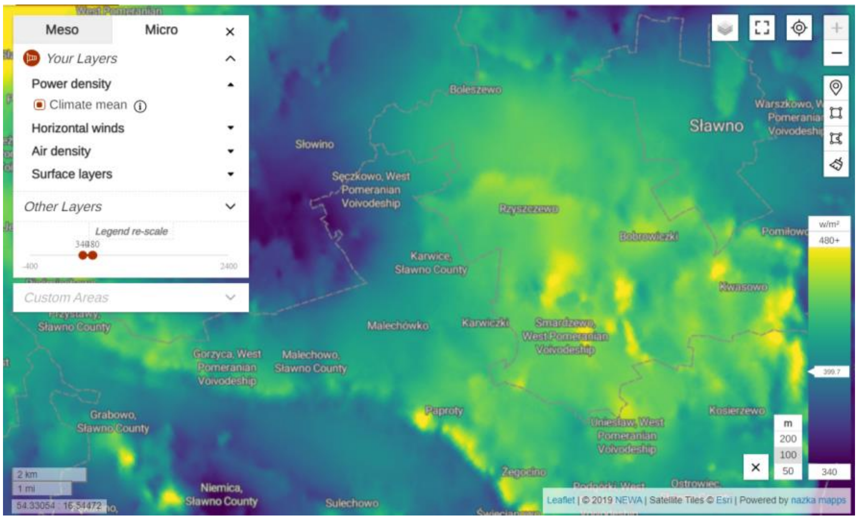


*Figure 2c: Power Density of **Karwice** at 100m – Micro Scale (350 – 430 W/m^2)*

B) Lebork

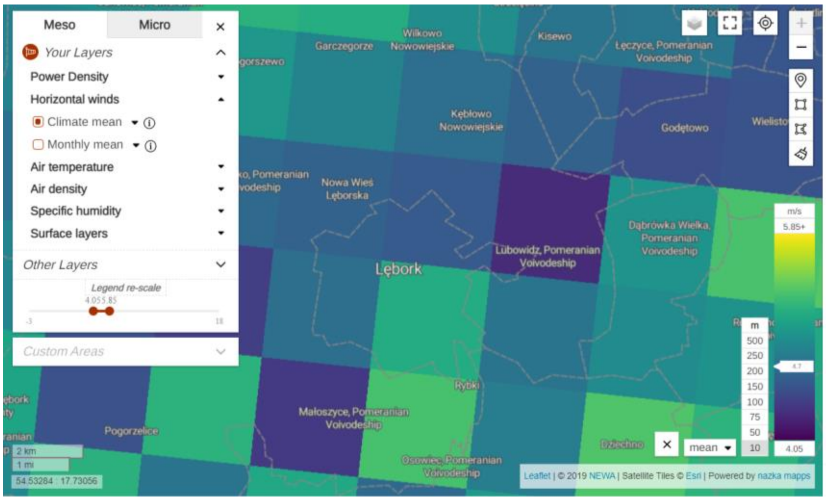


*Figure 3a: Wind speed of **Lebork** at 10m – Meso Scale (Average windspeed = 5.16 m/s)*

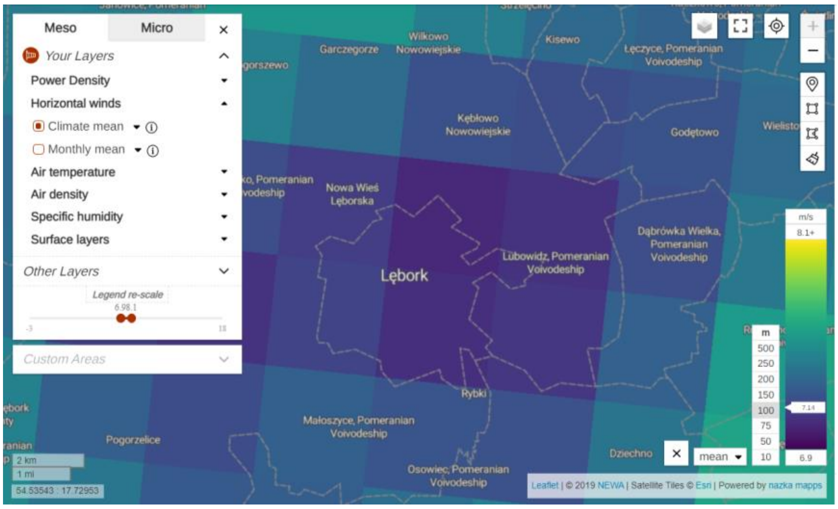


*Figure 3b: Wind speed of **Lebork** at 100m – Meso Scale (Average windspeed = 7.06 m/s)*

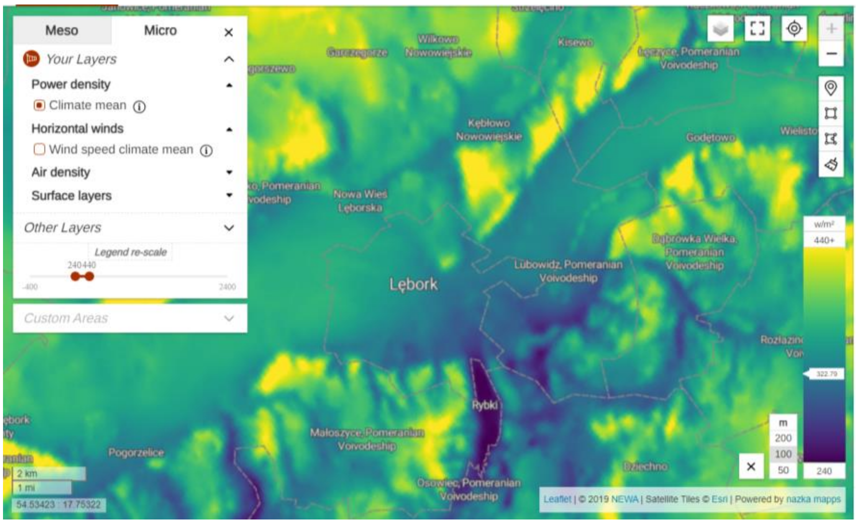


*Figure 3c: Power Density of **Lebork** at 100m – Micro Scale (272 – 415 W/m²)*

C) Koszalin

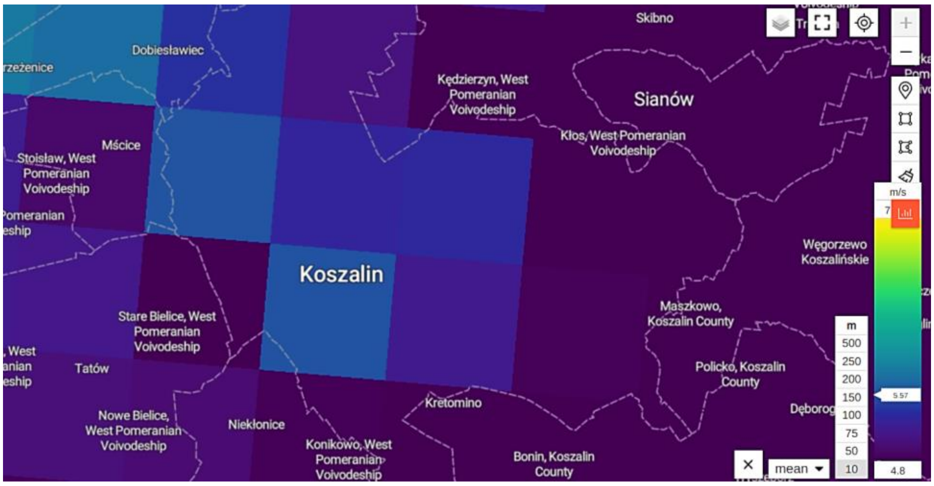


*Figure 4a: Wind speed of **Koszalin** at 10m – Meso Scale (Average windspeed = 7.12 m/s)*

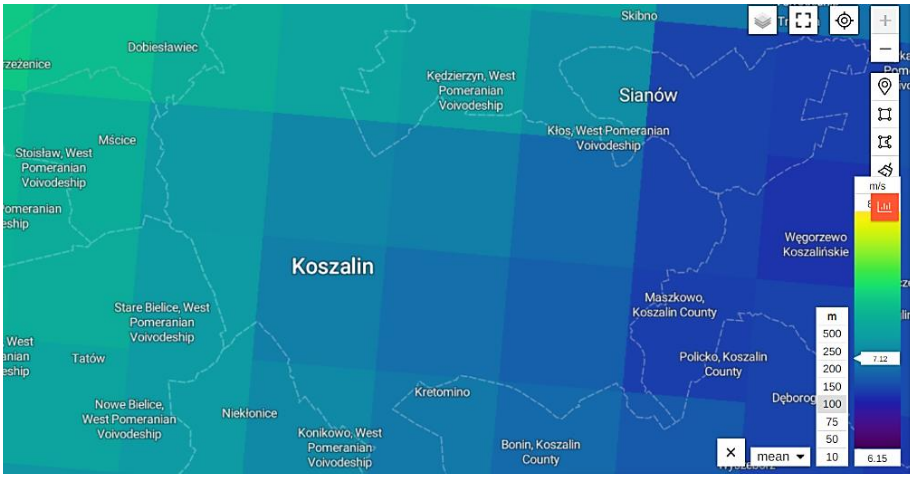


*Figure 4b: Wind speed of **Koszalin** at 100m – Meso Scale (Average windspeed = 5.57 m/s)*

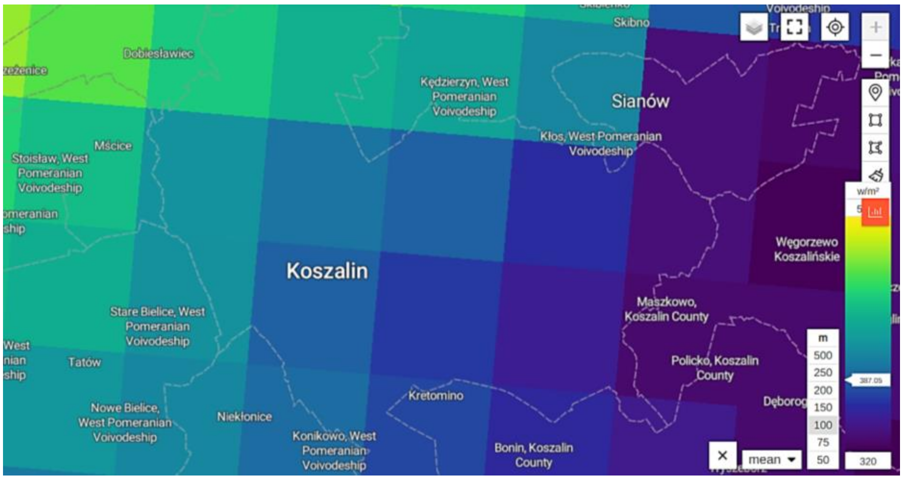


*Figure 4c: Power Density of **Lebork** at 100m – Micro Scale (387.05 W/m^2)*

D) Kołobrzeg

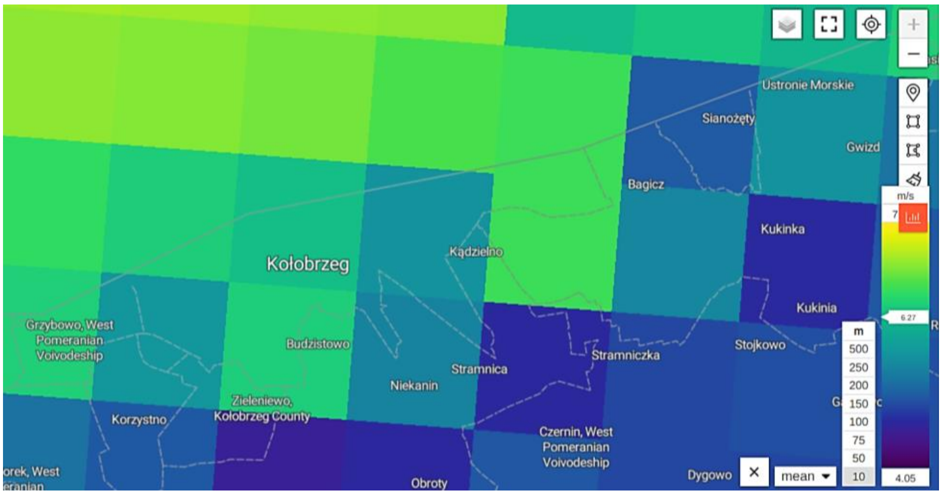


*Figure 5a: Wind speed of **Kołobrzeg** at 10m – Meso Scale (Average windspeed = 6.27 m/s)*

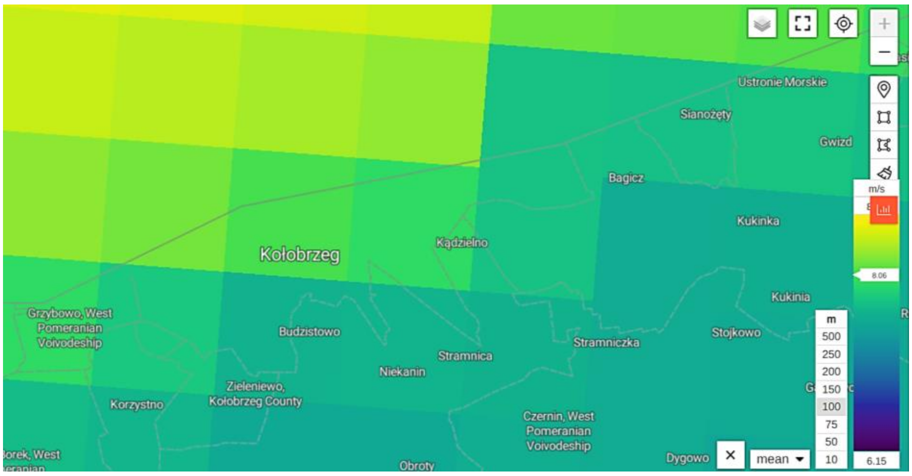


*Figure 5b: Wind speed of **Kołobrzeg** at 100m – Meso Scale (Average windspeed = 8.06 m/s)*

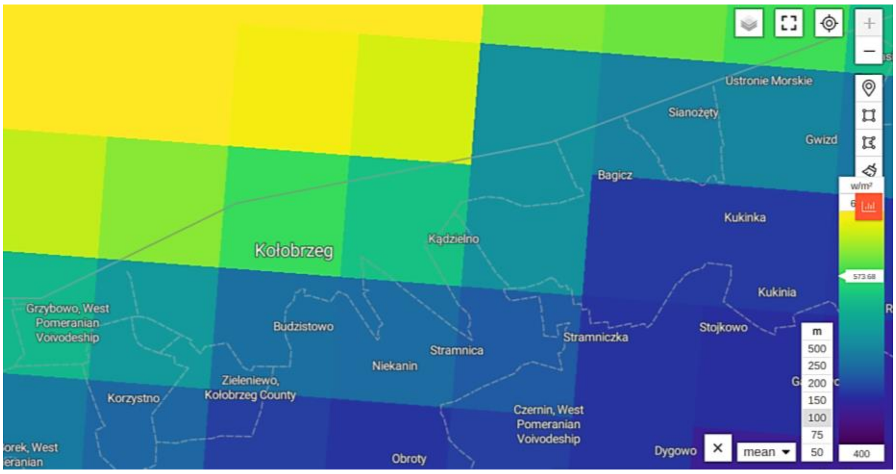


*Figure 5c: Power Density of **Kołobrzeg** at 100m – Micro Scale (573.68 W/m^2)*

E) Darlowek

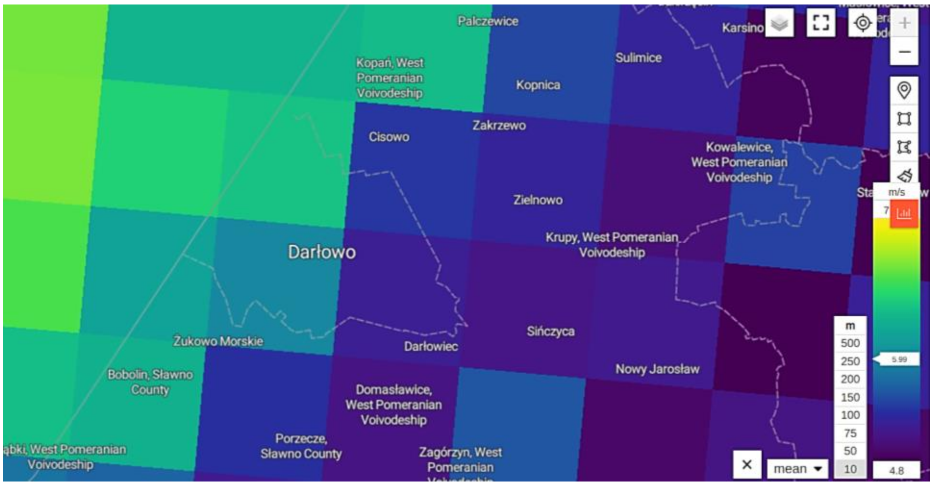


*Figure 6a: Wind speed of **Darlowek** at 10m – Meso Scale (Average windspeed = 5.99 m/s)*

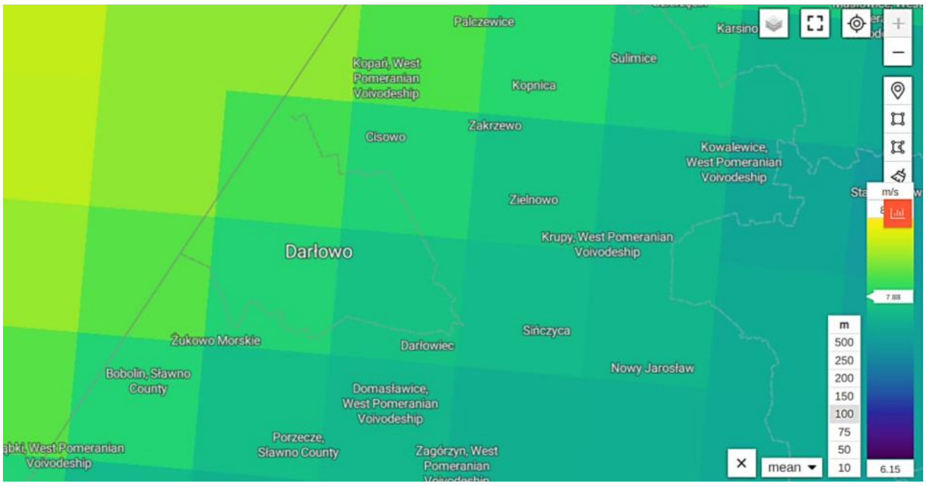


*Figure 6b: Wind speed of **Darlowek** at 100m – Meso Scale (Average windspeed = 7.88 m/s)*

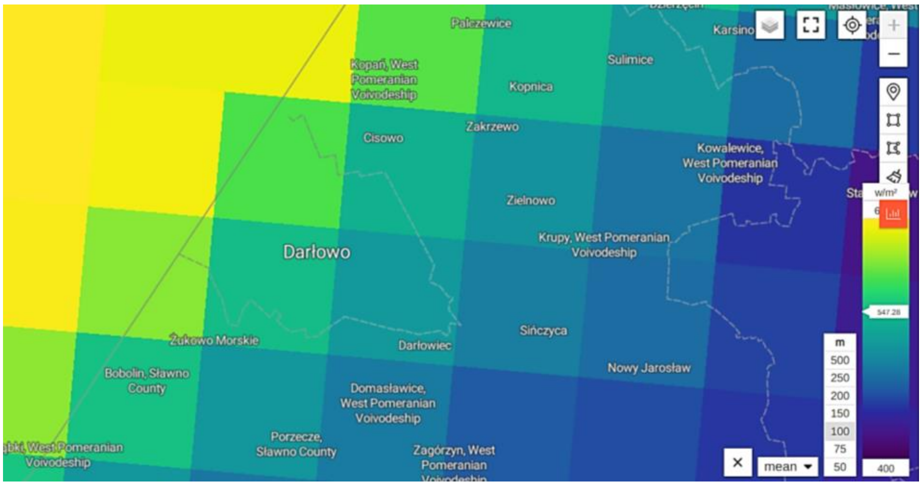


*Figure 6c: Power Density of **Darlowek** at 100m – Micro Scale (547.28 W/m^2)*

Section A

LĘBORK

Station Analysis

Lebork is located in latitude 54.55 and longitude 17.75. it has an elevation of 17m with meteorological station ID of 121250. Like Karwice, in Lębork, the summers are comfortable and partly cloudy, and the winters are long, freezing, snowy, windy, and mostly cloudy. Over the course of the year, the temperature typically varies from 25°F to 71°F and rarely below 9°F or above 82°F as depicted in Figure 1c. Figure 1d shows the average high and low temperature in Lębork. The warm season lasts for 3.5 months, from May 25 to September 10, with an average daily high temperature above 64°F. The hottest month of the year in Lębork is July, with an average high of 71°F and low of 53°F. The cold season lasts for 3.9 months, from November 18 to March 15, with an average daily high temperature below 41°F. The coldest month of the year in Lębork is January, with an average low of 26°F and high of 34°F. As shown in Figure 1e, rain falls throughout the year in Lębork. The month with the most rain in Lębork is July, with an average rainfall of 2.4 inches. While the month with the least rain in Lębork is February, with an average rainfall of 0.7 inches.

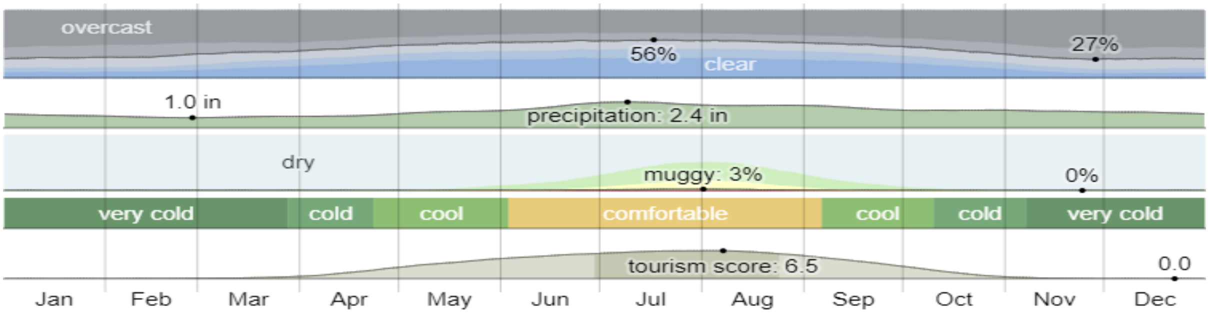


Figure 7a: Climate in Lębork

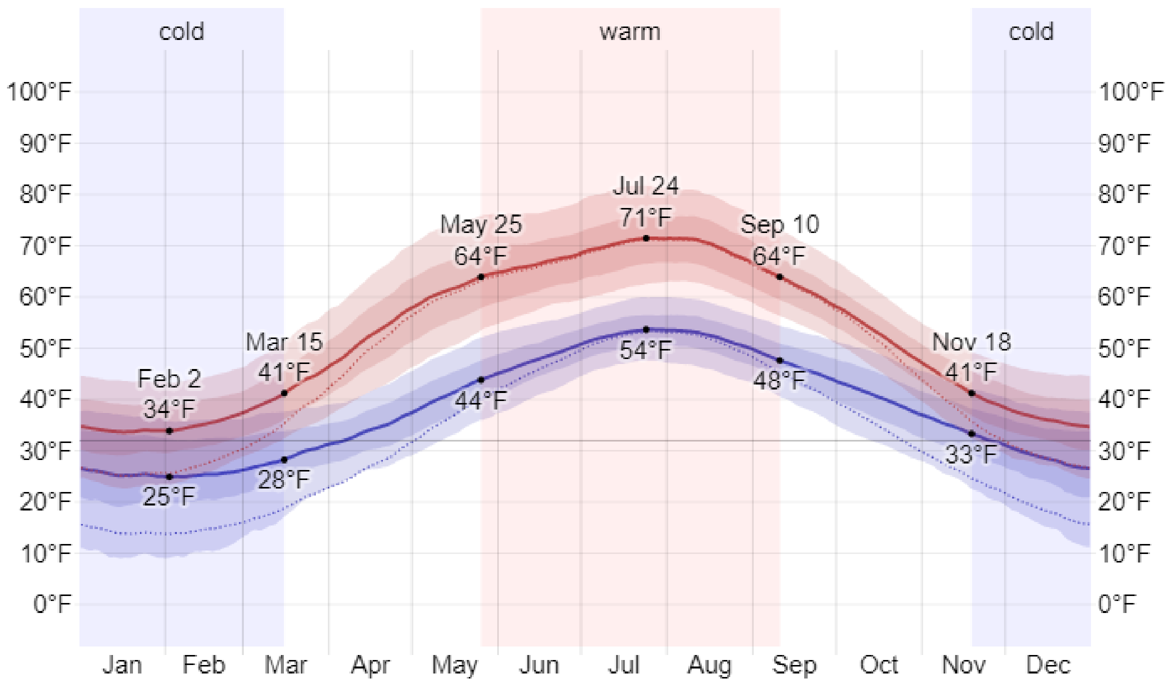


Figure 7b: Average High and Low Temperature in Lębork

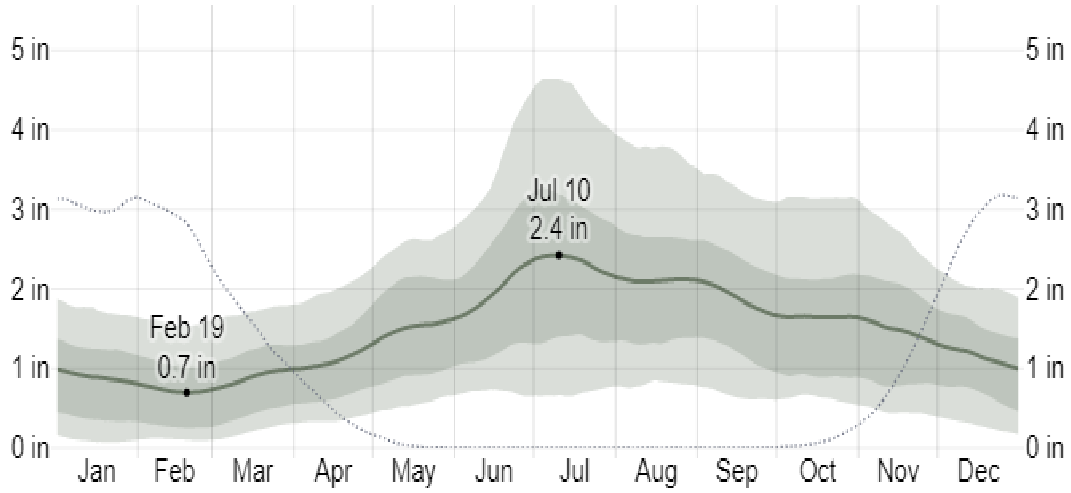


Figure 7c: Average Monthly Rainfall in Lębork

3.0 Analysis of Lebork Meteorological Station

The analysis began with the extraction of Lebork wind data from the repository of meteorological data for various sites in Poland. The structure of the data was validated and checked, and formatted to appropriate time stamp, and was also converted into a metmast object using the library bReeze.

3.1 Data Availability and Cleaning

A) Before Cleaning – Availability Check

Attempt was made to check the availability of the dataset – to verify whether the availability was above the 75% threshold. The result depicted in Figure 8a with the calendar plot in Figure 9 revealed that prior cleaning, the availability of the data is 98.7% which is well above 75%. Nevertheless, attempt was further made to clean the data. That is, to check whether all values printed in the calendar plots are valid -whether there are missing data inputted as 99999. To achieve this, a summary report of the data was plotted. The result depicted in Figure 8b revealed that some missing values (inputted as -99999) are present in the dataset, indicating that the data requires some cleaning before further analysis can be carried out.

```
     availability effective period total period
              [%]              [d]          [d]
set1         98.7              360        364.8

number of daily samples:
set1
            %  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22
2014-01 100.0 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24
2014-02  99.7 24 24 24 24 24 24 24 24 24 24 24 24 24 23 24 24 24 23 24 24 24 24
2014-03  99.6 24 24 22 24 24 24 24 24 24 23 24 24 24 24 24 24 24 24 24 24 24 24
2014-04  99.6 24 24 24 24 24 24 24 24 23 24 22 24 24 24 24 24 24 24 24 24 24 24
2014-05 100.0 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24
2014-06  96.4 24 24 24 24 24 24 24 24 24 15 17 22 24 24 24 23 24 24 24 24 24 24
2014-07  98.4 24 24 24 24 24 24 24 24 23 23 24 17 23 24 24 24 24 24 24 24 24 23
2014-08  94.0 24 24 23 24 24 24 24 24 24 24 15  0 15 24 23 24 24 24 24 24 23 24
2014-09  99.9 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 23
2014-10  97.7 24 24 24 24 24 24 24 24 24 24 24 24 24 23 24 17 17 24 23 23 24 24
2014-11  99.7 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 22 24 24 24 24 24 24
2014-12  98.9 24 24 24 24 24 20 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24
        23 24 25 26 27 28 29 30 31
2014-01 24 24 24 24 24 24 24 24 24
2014-02 24 24 24 24 24 24
2014-03 24 24 24 24 24 24 24 24 24
2014-04 24 24 24 24 24 24 24 24
2014-05 24 24 24 24 24 24 24 24 24
2014-06 24 24 20 24 22 24 23 24
2014-07 24 24 24 24 24 24 24 23 24
2014-08 24 24 24 24 24 24 24 24 24
2014-09 24 24 24 24 24 24 24 24
2014-10 24 24 24 24 24 24 24 24 24
2014-11 24 24 24 24 24 24 24 24
2014-12 24 24 24 24 24 24 23 24 21
```

Figure 8a: Lebork Station's Data Availability Before Cleaning

```
> summary(metmast$sets$set1$data$v.avg)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
 -99999       2       3   -2416       4      15
> 
```

Figure 8b: Summary of Lebork Station's Data Availability (Before Cleaning)

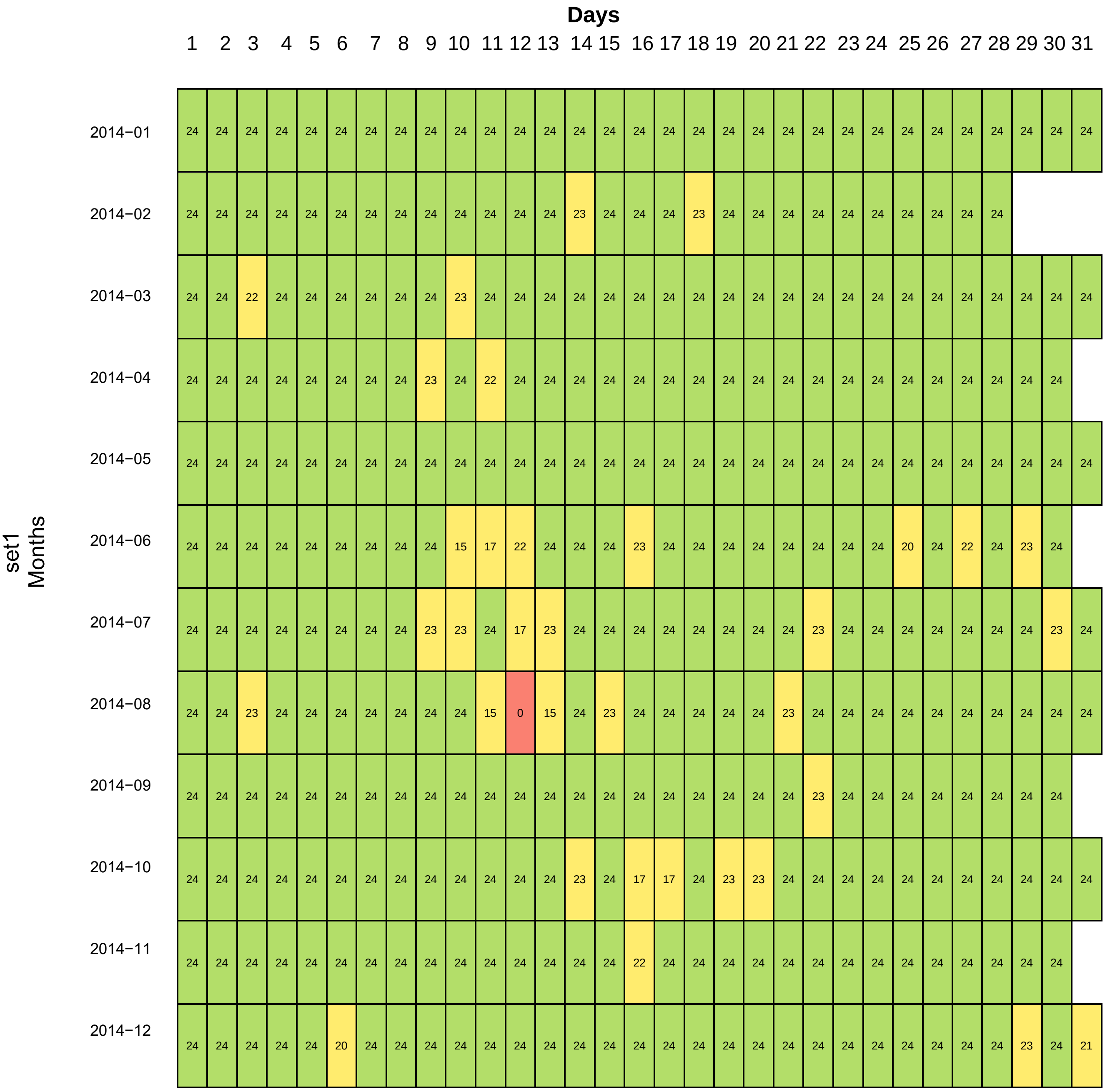


Figure 9: Lebork Station Daily Availability Calendar Plot Before Cleaning

B) Cleaned Data

To clean the data, appropriate codes were initiated and the results are depicted in Figures 10a, 10b, and 11. From figure 10a, it is obvious that the availability after cleaning the datasets reduced to 93.5% against the 98.7% in the uncleaned data. This is as a result of the of missing information formerly considered as part of the values in the uncleaned data. From Figure 10b, it can be observed that 455 data values initially recorded as -9.9999 were replaced with NA in the dataset. However, The 93.5% availability shows that the data is valid – since it is well above 75%. Hence further analysis were carried out on the dataset to estimate the wind resource of the wind fam using the dataset of the Lebork meteorological station. Meanwhile, from Figure 10b, the mean values of wind speed is 3.323, the maximum value is 15, while the median, first quantile and third quantile are 3, 2 and 4m/s respectively.

```
     availability effective period total period
              [%]              [d]          [d]
set1         93.5            341.1        364.8

number of daily samples:
set1
           %  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22
2014-01 98.4 24 24 24 23 24 24 24 24 24 24 24 24 24 23 23 23 24 23 23 23 23 24
2014-02 98.2 24 24 23 24 23 23 23 24 24 24 24 24 24 23 24 24 24 23 24 24 23 22
2014-03 98.3 24 24 22 24 24 24 24 24 24 23 22 23 24 24 24 24 24 24 24 24 24 24
2014-04 94.9 24 23 24 22 24 23 24 23 23 24 20 22 23 24 24 23 24 24 21 24 24 22
2014-05 95.0 23 19 21 23 24 23 24 22 24 24 24 24 24 23 18 21 23 22 24 22 19 24
2014-06 93.3 23 24 23 22 24 23 24 22 24 14 17 22 24 24 22 23 21 24 24 24 24 24
2014-07 93.0 22 22 24 21 24 24 23 23 23 23 24 17 23 23 23 22 22 24 23 24 22 19
2014-08 70.0 24 21 23 16  0  1  0  0  0  0  0  0 15 24 23 24 24 24 24 24 23 24
2014-09 94.4 24 20 18 21 23 24 23 23 24 24 23 22 24 24 24 23 23 24 24 23 22 23
2014-10 93.4 21 22 23 24 23 23 24 24 24 24 24 23 23 22 22 13 17 24 23 23 20 23
2014-11 96.7 24 24 24 24 24 23 23 24 23 24 22 23 24 23 23 22 23 22 23 22 24 22
2014-12 96.4 24 24 18 24 23 20 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24 24
        23 24 25 26 27 28 29 30 31
2014-01 23 23 23 24 24 23 24 24 24
2014-02 23 24 24 24 23 23
2014-03 23 23 24 24 24 23 22 23 23
2014-04 18 24 24 24 19 21 21 23
2014-05 24 24 23 24 23 24 24 24 22
2014-06 24 24 17 22 19 23 23 24
2014-07 20 19 21 23 23 23 24 22 22
2014-08 24 23 23 24 24 23 20 22 24
2014-09 22 24 24 21 24 24 21 17
2014-10 24 24 24 24 24 24 23 19 20
2014-11 24 24 24 23 21 24 24 22
2014-12 24 24 22 21 24 22 18 24 21
```

Figure 10a: Lebork Station's Data Availability After Cleaning

```
> summary(metmastclean$sets$set1$data$v.avg)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
  1.000   2.000   3.000   3.323   4.000  15.000     455
>
```

Figure 10b: Summary of Lebork Station's Data Availability (After Cleaning)

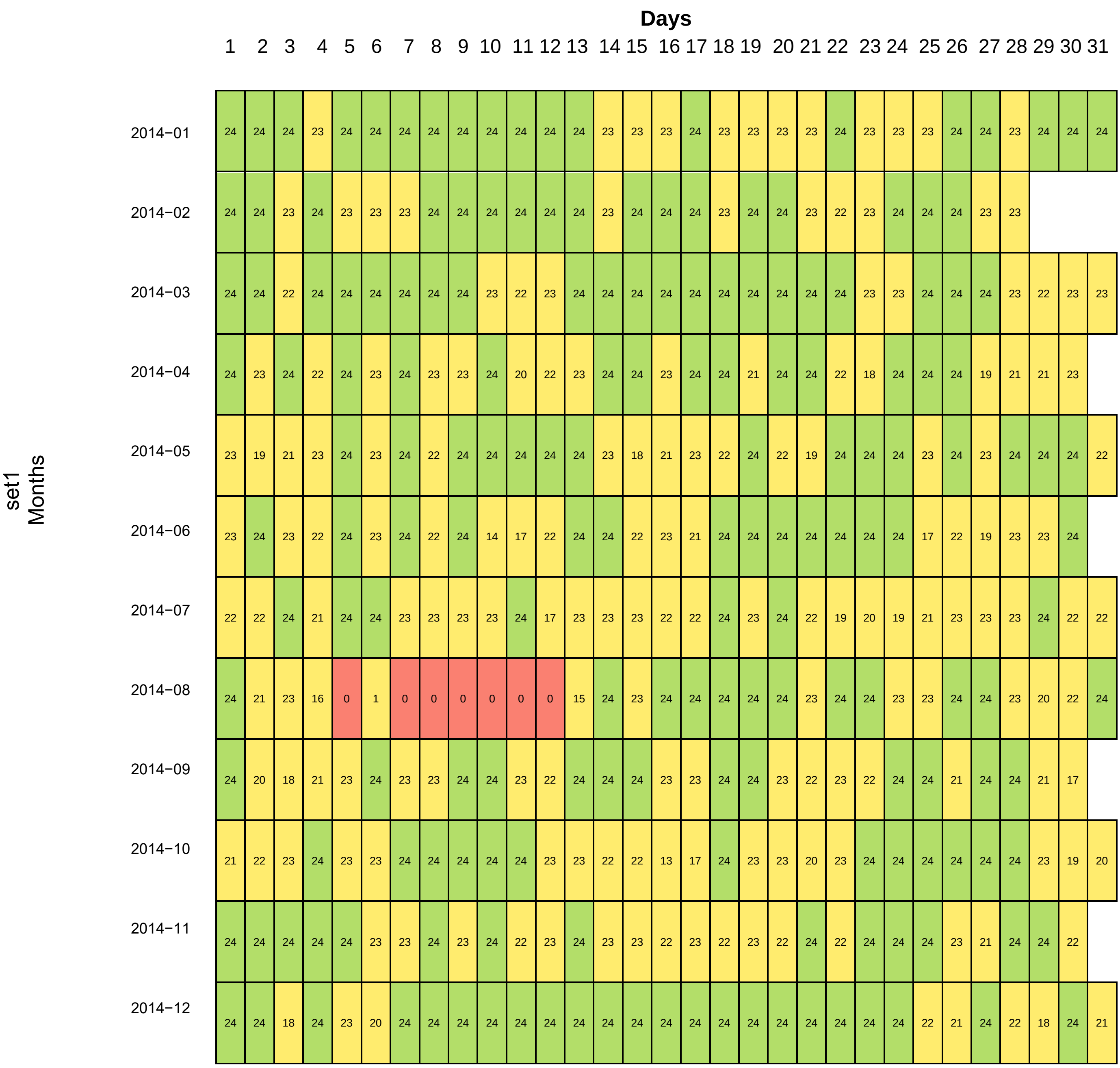


Figure 11: Lebork Station Daily Availability Calendar Plot After Cleaning

Figure 11 reveals the calendar plots of the cleaned dataset of Lebork meteorological station. Days with magenta colour indicate days where there are no wind information, yellow colour indicates days where there is no wind information for all 24 hours (that is, days where there is missing wind data for one or more hours), while green colours indicates days that has wind information for the whole 24 hours within a day. From Figure 11, out of the 365 days, seven (7) days within the month of August essentially has no wind information. 176 days has one or more hours of missing data, while the remaining days has data for all the 24 hours in a day.

3.2 Time Series of Wind Measurements

After validating and cleaning the datasets, attempts were made to plot the average wind speed and average wind direction for one year, month, week, and a day. The various plots obtained are therefore presented in this section.

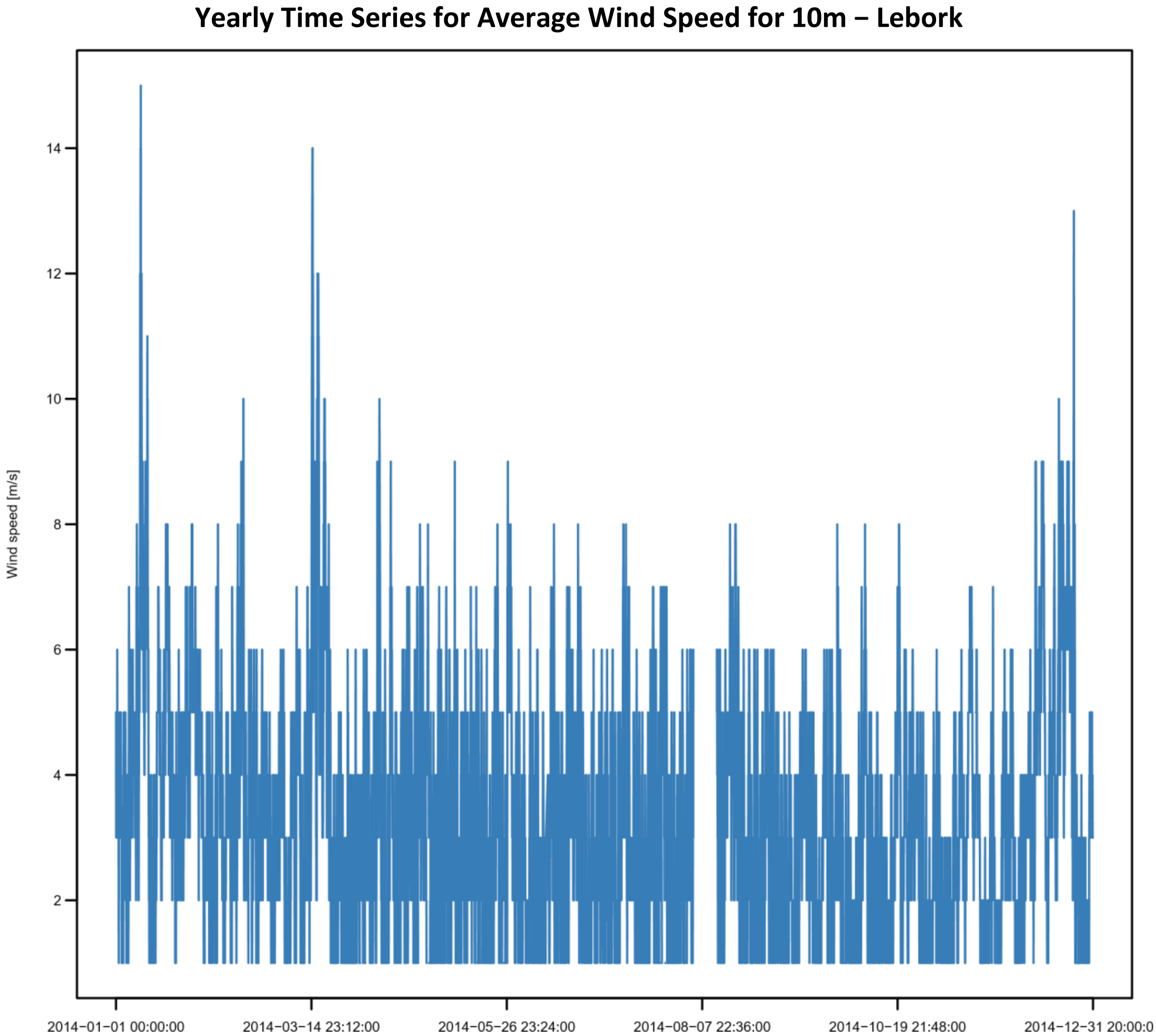


Figure 12: Average wind speed for the year 2014 in Lebork Meteo Station

As depicted in Figure 1, the average wind speed in the study area varies all through the months in the year with obvious increase and decease in the wind speed values. The highest recorded average wind speed occurred around the month of January with about 15m/s followed by the 14m/s obtained around March, and about 13m/s obtained in December. The calmest days of the year occur around August. The difference in the observed pattern of windspeed can be attributed to differences in seasons as cold seasons as notorious for high wind speeds when compared with the warmer summer seasons. As WindLogger, (2022) affirmed, temperature differences between air masses lead to pressure differences, and this produces wind. The winter brings higher temperature gradients, especially when cold fronts move from polar regions, and this causes wind speeds that are higher than normal rates.

Monthly Time Series for Average Wind Speed for 10m – Lebork

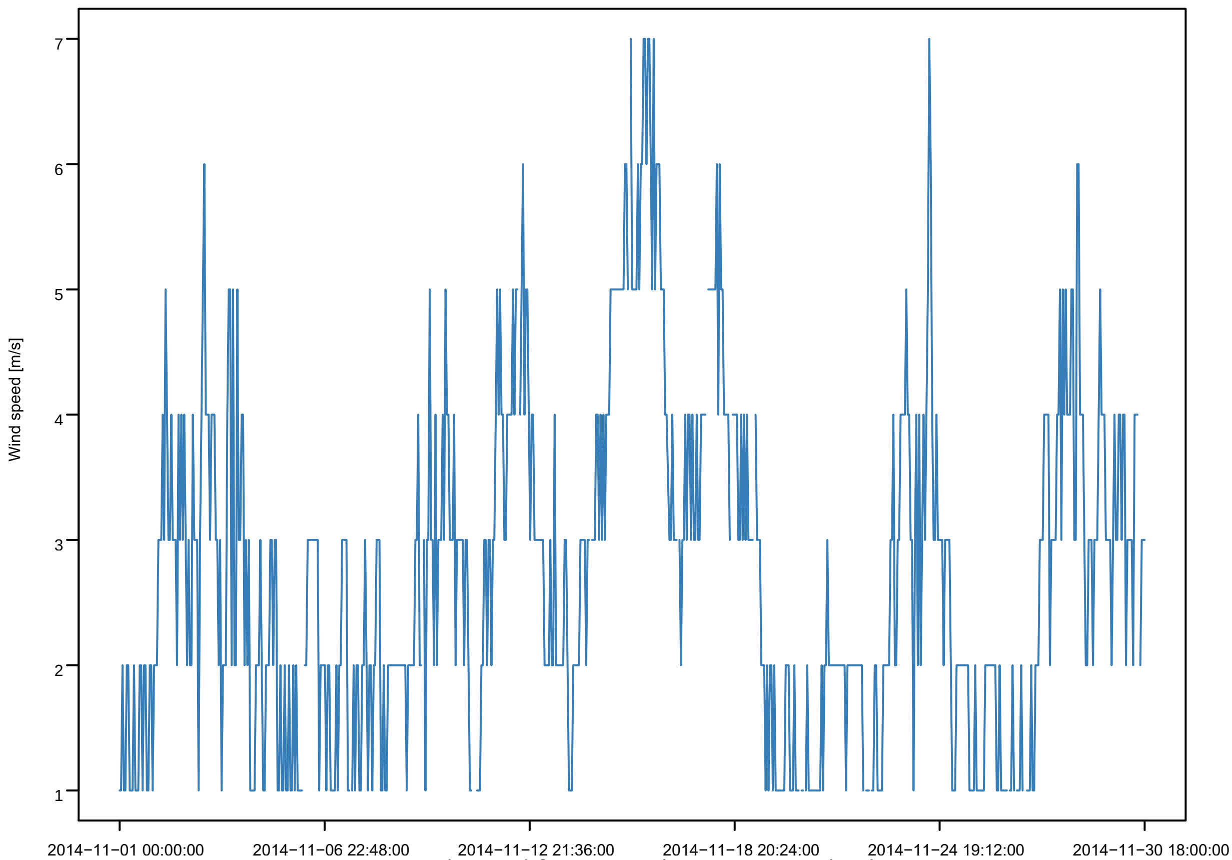


Figure 13: Average wind speed for November 2014 in Lebork Meteo Station

Weekly Time Series for Average Wind Speed for 10m – Lebork

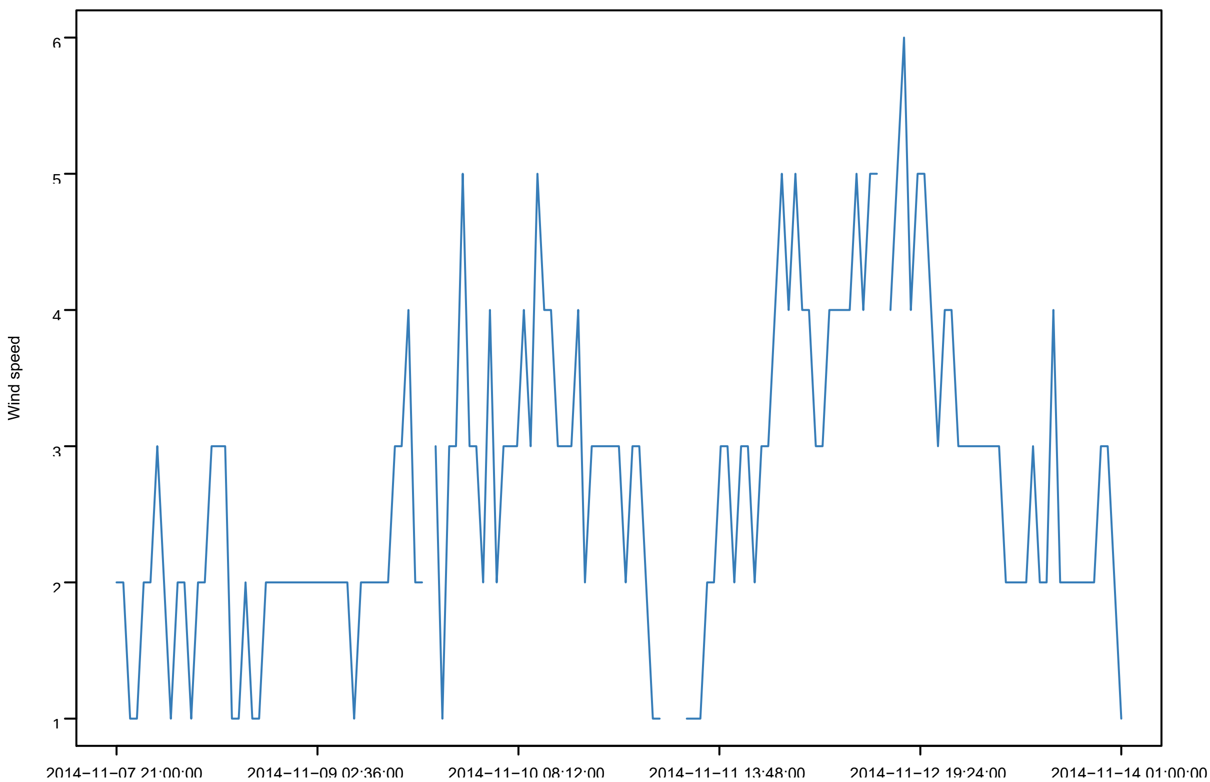


Figure 14: Average wind speed for a Week in November 2014 in Lebork Meteo Station

Figure 13 reveals average wind speed data recoded for November 2014. Also in this plot, there is marked variations in the average windspeed values, however it can be observed that the highest wind speed occurred between the 15th and 24th day of the month with more than 7m/s followed by 6m/s which occurred around the 5th, 12th, 18th and 29th days of the month.

A closer look at a week data depicted in Figure 14, reveals that the average wind speed for a week within November. The data also follows similar pattern as there is observed variations in the average wind speed in each hour of the days in the week. Though with this plot, it is obvious the average wind speed increase with time and days, which could perhaps be a result of reduced temperature and increased cold normally associated with November in Poland as the day increases. Earlier days in November are normally warmer, while latter days are generally colder, hence there is likelihood the average windspeed in the earlier days will be considerably lower than that of the latter days as obviously revealed in Figure 14.

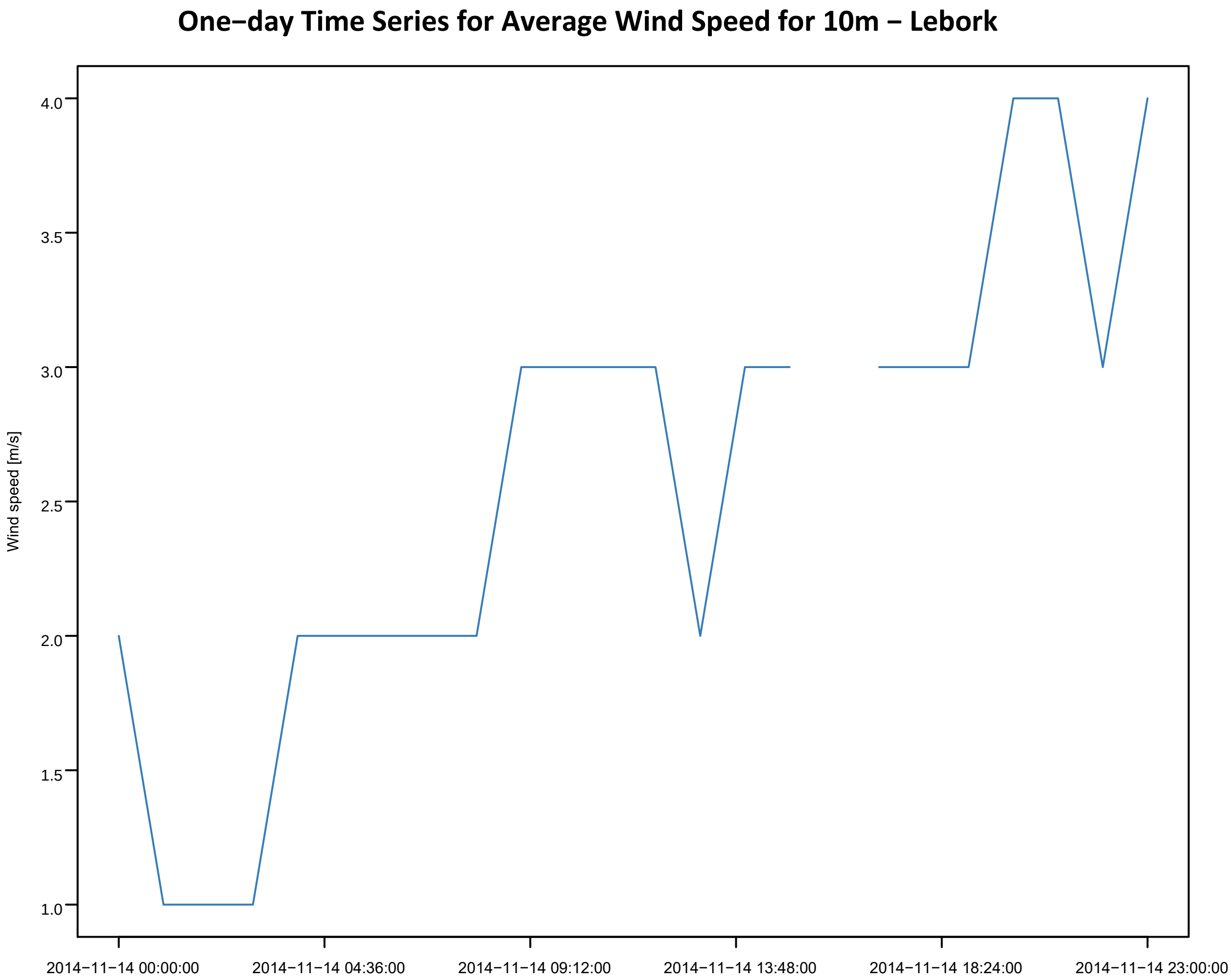


Figure 15: Average wind speed for day 14th, November, 2014 in Lebork Meteo Station

Figure 15 reveals the hourly average wind speed recorded for a day, precisely 14th Nvember 2014 between the hours of 12 noon till the end of the day. Generally, the time series revealed that wind speed increase with increasing hours of the day (from the start time) with the highest average speed being 4 m/s and the lowest being around 1m/s. Variations in the warming of the air caused by differences in light intensity during the days brought about the differences in the wind speed recorded for that day at Lebork.

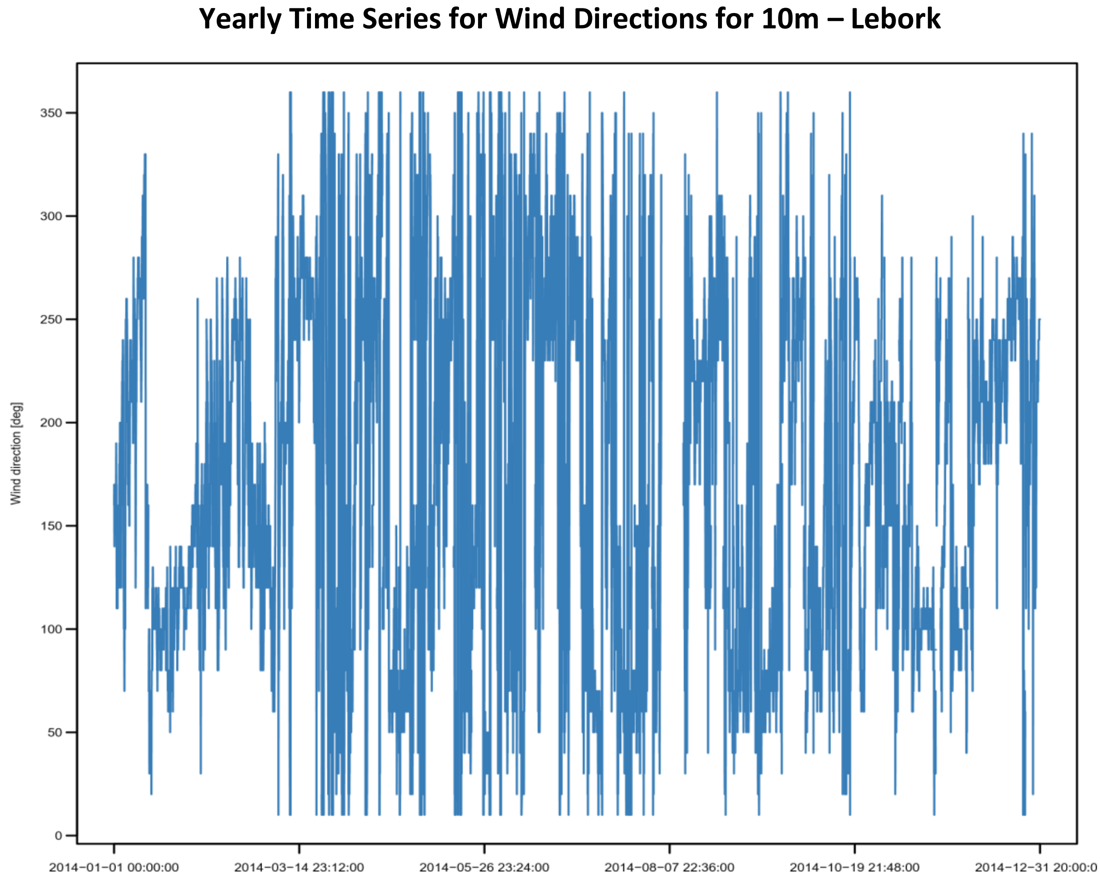


Figure 16: Average wind speed for the year 2014 in Lebork Meteo Station

Figure 16 depicts the time series of the average wind speed direction for the year 2014. As shown the plot the wind dierection varies over over the period considered. Between March to October, the wind direction changes to a degree as hgh as 350^0, which also happens to be periods where there are lower wind speeds shown in Figure 12. The directional changes in wind direction in winter months are considerebly lower than the other months – and these winter months happens to be months with the strongest wind speeds as depicted in Figure 12. It is worth nothing that the bulk of the wind blows bteween 300^{o}C and 70^{o}C this is obvious in Figure 17 which shows the average wind speed for November 2014.

Monthly Time Series for Average Wind Direction for 10m – Lebork

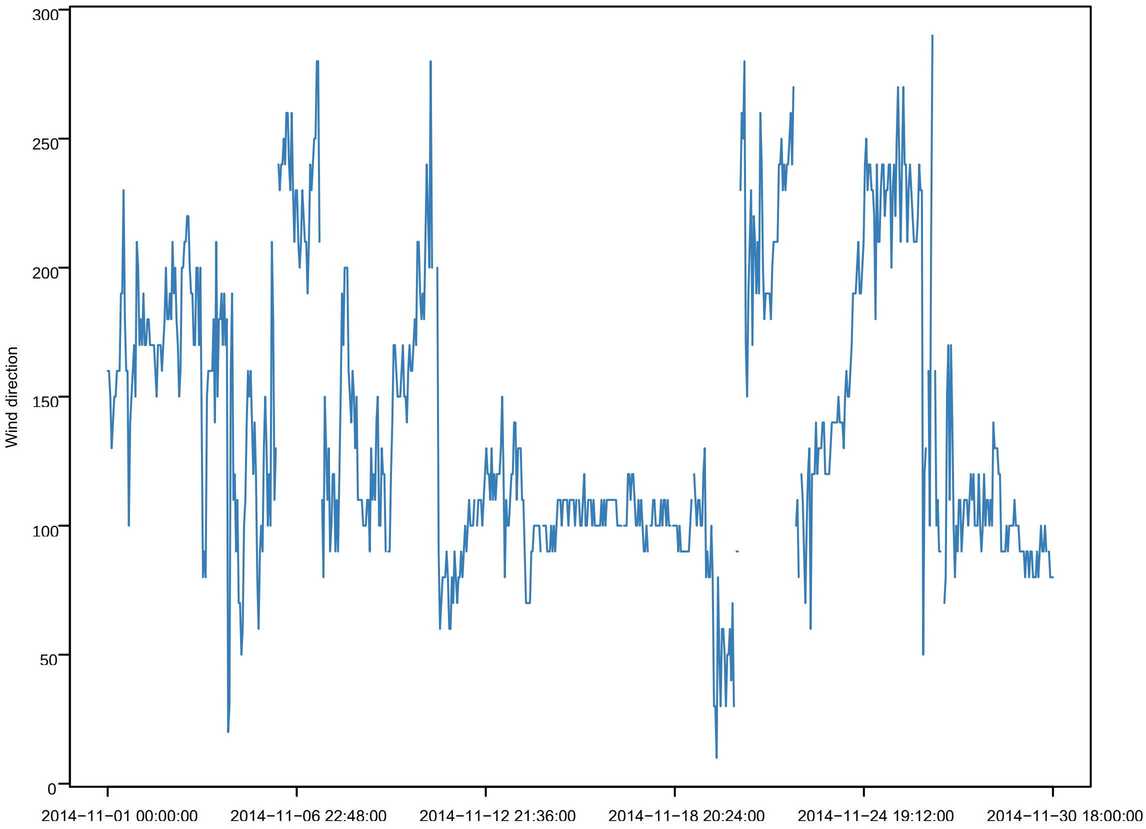


Figure 17: Average wind direction for November 2014 in Lebork Meteo Station

Weekly Time Series for Average Wind Directions for 10m – Lebork

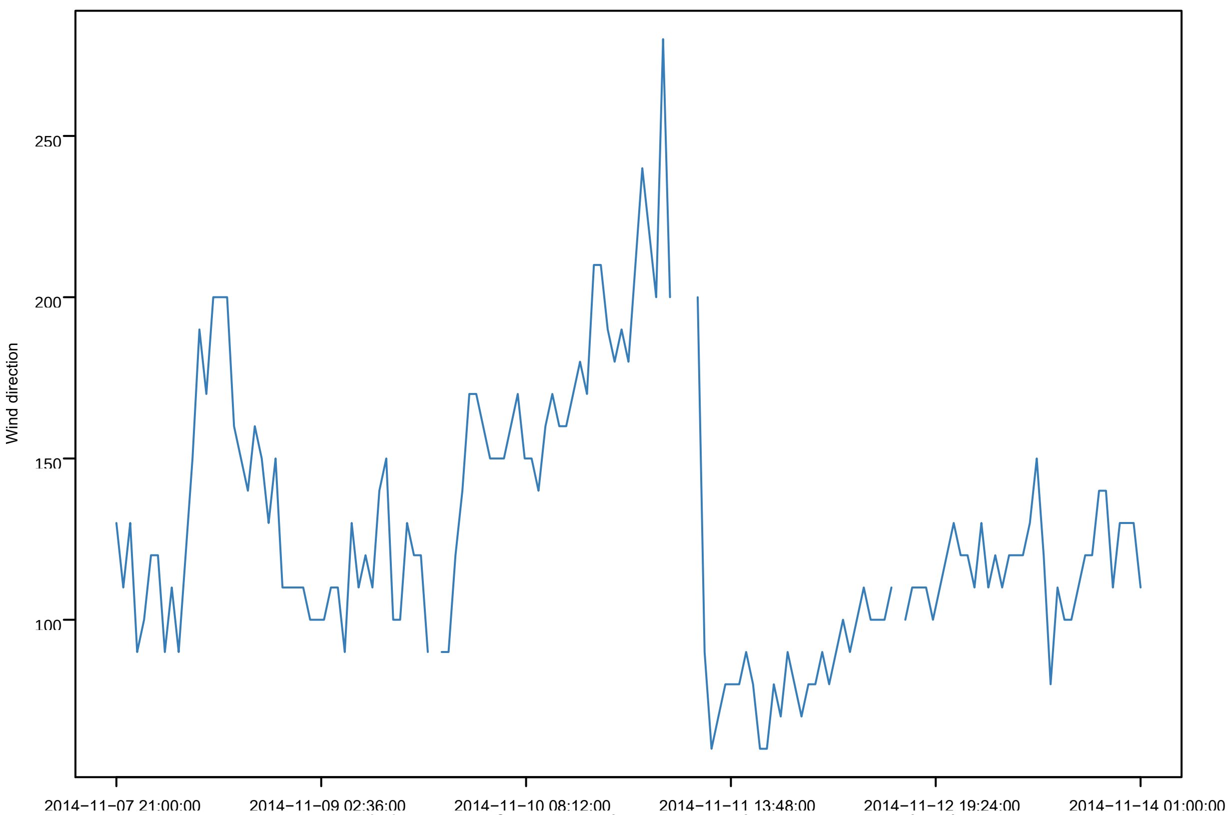


Figure 18: Average wind direction for a Week in November 2014 in Lebork Meteo Station

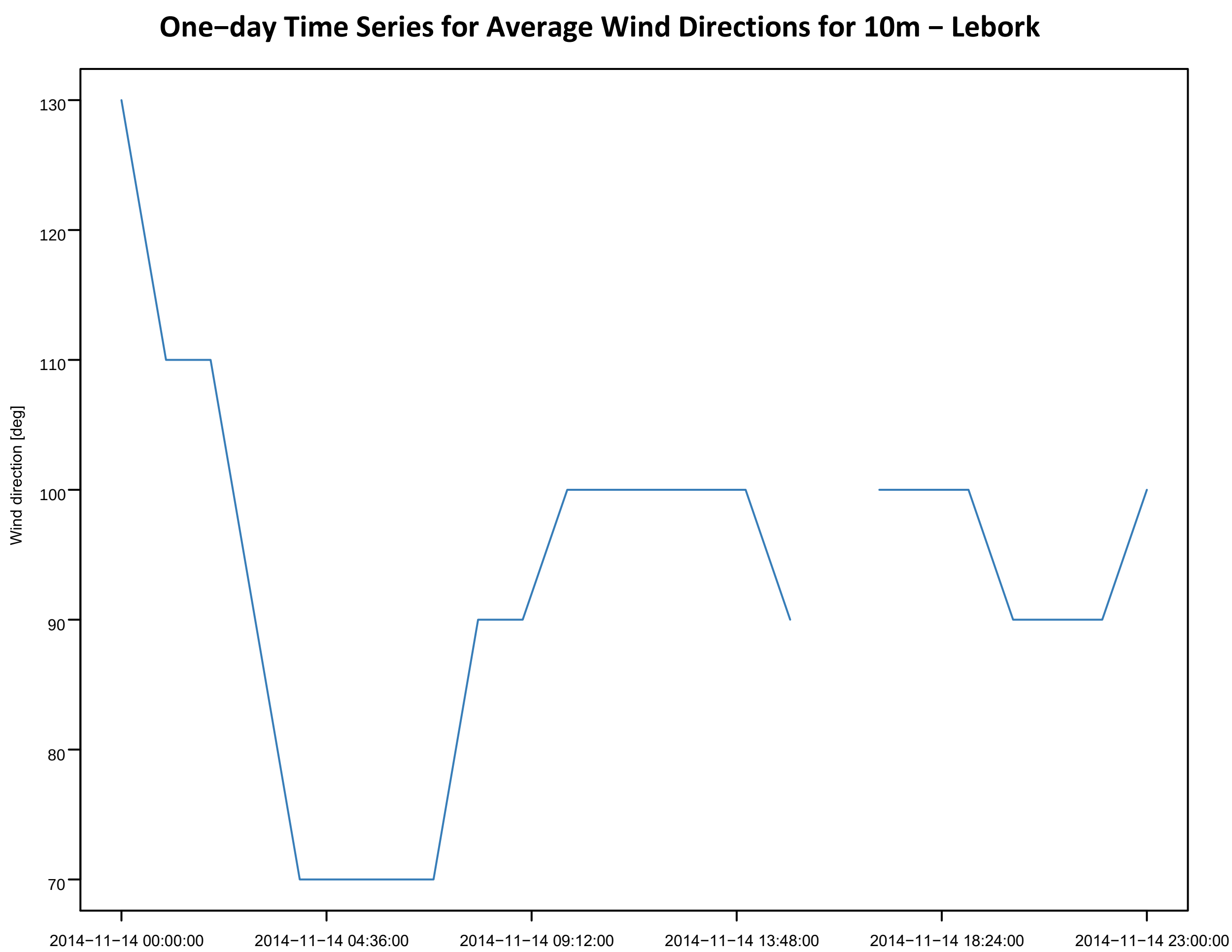


Figure 19: Average wind speed for day 14th, November, 2014 in Lebork Meteo Station

Figures 18 and 19 depicts the average wind directions for a week and one day in Lebork station. As depicted in the Figures, the variations in the ranges of wind directions changes with reduced days. That is, in Figure 18, which represents average wind direction for a week has the direction ranging from 50°C to about 300°C. while in Figure 19, the direction ranges between 70°C to 130°C.

3.3 Calculating and Plotting Statistics for Time Series (seasonal and diurnal changes)

A) Monthly Mean

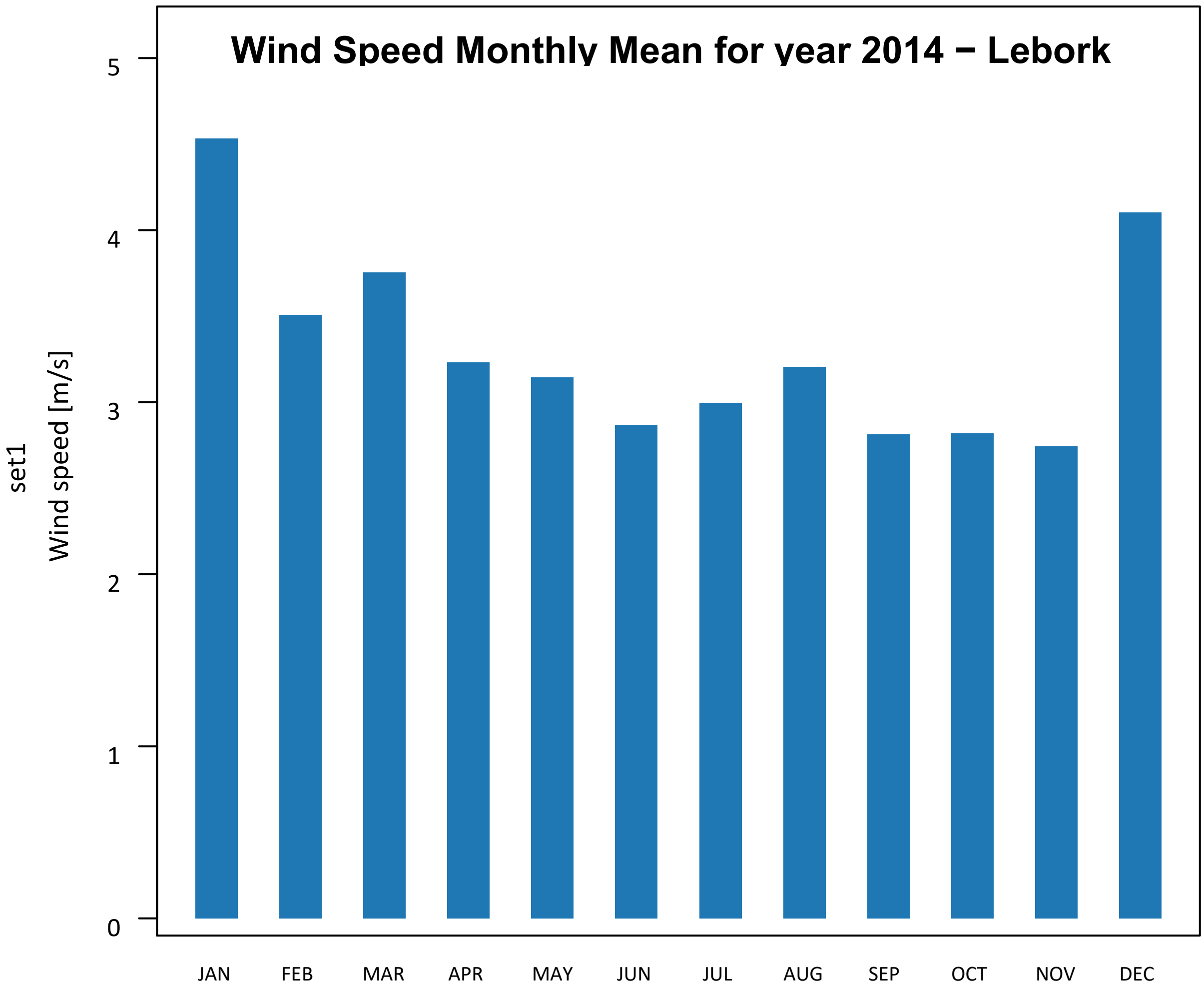


Figure 20: Monthly mean of wind speed in Lebork Meteo Station

Obviously from Figure 20, the highest mean of wind speed occurred in January with 4.533m/s, followed by December which accounts for 4.102 m/s. The months of March and February has 3.755 m/s, and 3.508m/s respectively. The lowest mean value of wind speed recorded occurred in the month of November with 2.743 m/s. Generally, the warmer months has lower mean wind speed when compared to the wetter months. The cumulative mean of all months is 3.310m/s The result obtained here validates the result obtained for the average wind speed time series depicted in Figure 12.

B) Monthly Standard Deviation

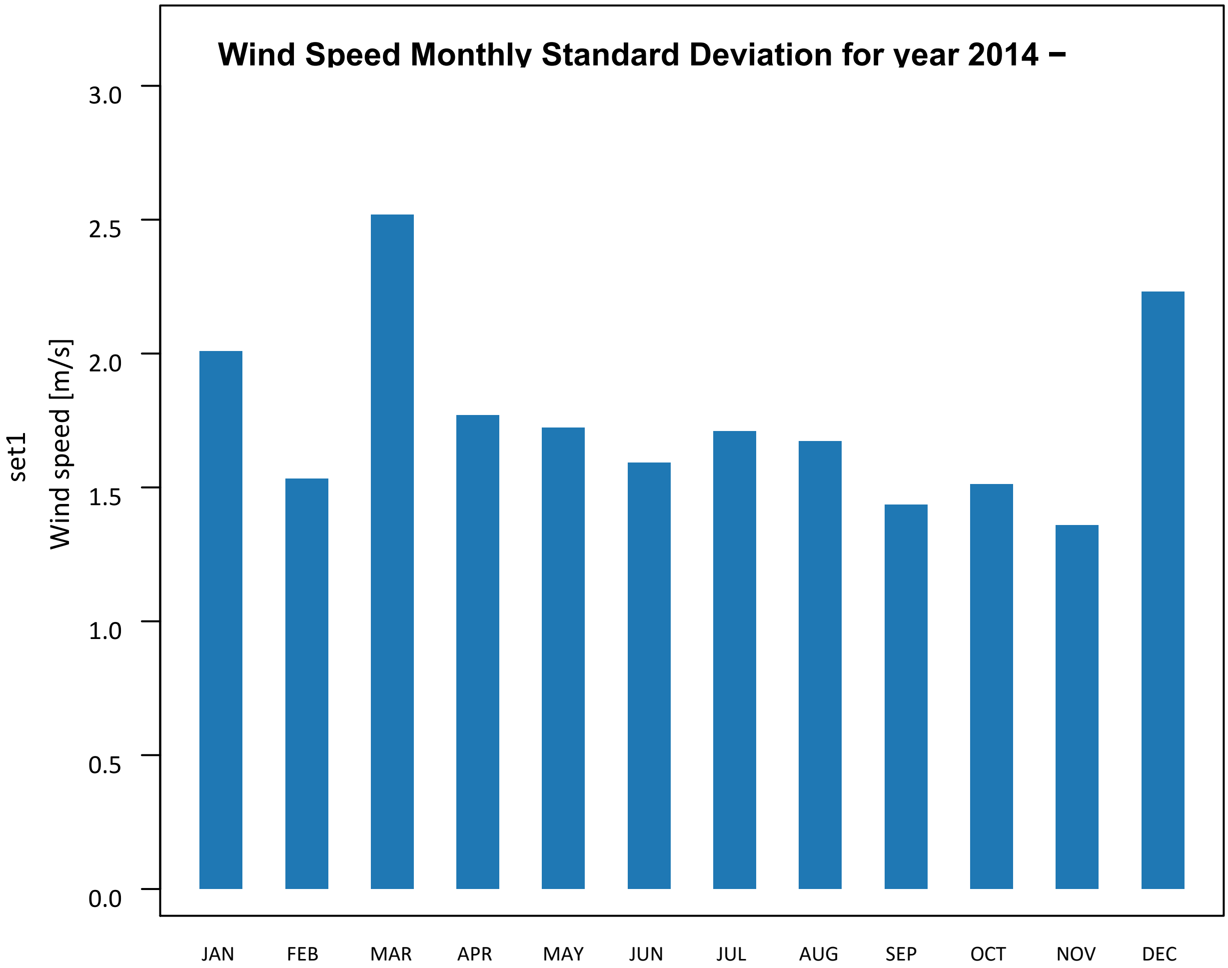


Figure 21: Monthly standard deviation of wind speed in Lebork Meteo Station

Standard deviation shows the degree at which the element of a dataset varies from the mean – how dispersed they are from the mean. As such, as seen in Figure 12, the highest variation (2.518m/s) in wind speed data recorded occurred in March. This is due to the fact that, the month of march is a transition month, from which the season changes from winter to spring, consequently affecting the speed of wind. The next month with higher deviation of wind speed to the mean is December – with a standard deviation value of 2.230 m/s – the reason for this could also be attributed to the transition to winter season that is often associated with the month of December in Poland. The third month with higher standard deviation is January with 2.009 m/s. The remaining months have standard deviation values below 1.9m/s.

C) Monthly Minimum

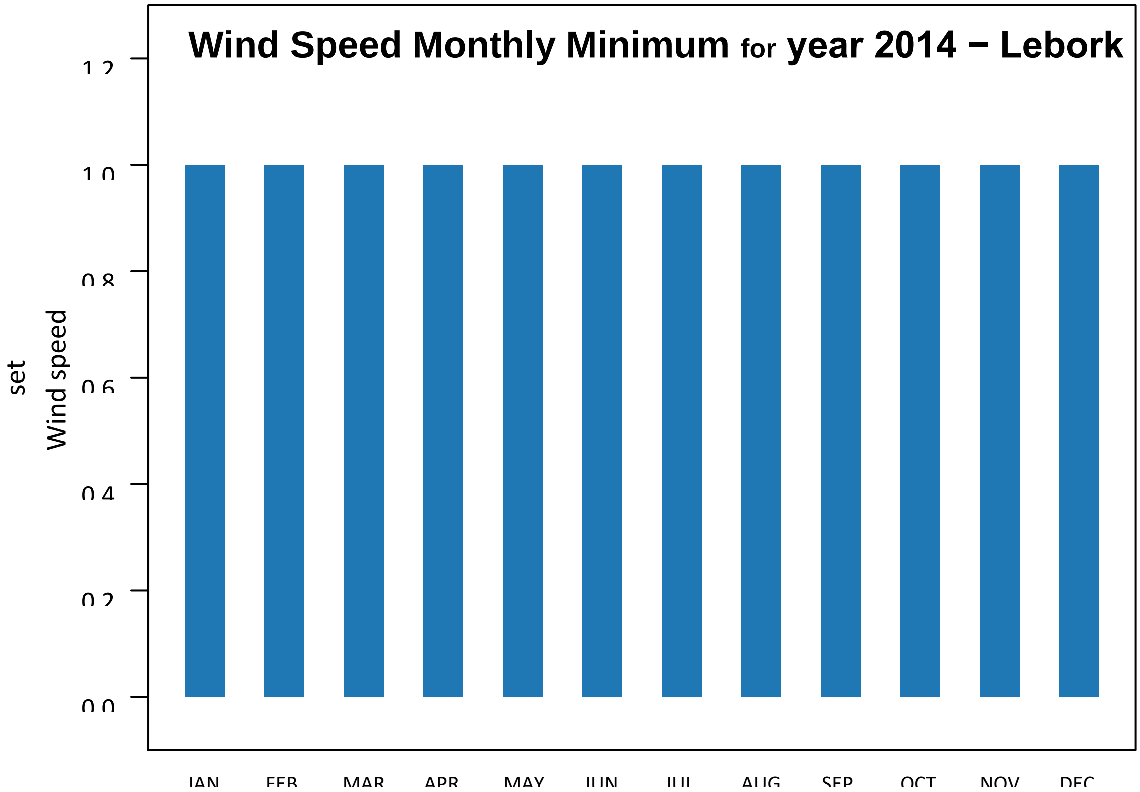


Figure 22: Monthly minimum of wind speed in Lebork Meteo Station

D) Monthly Maximum

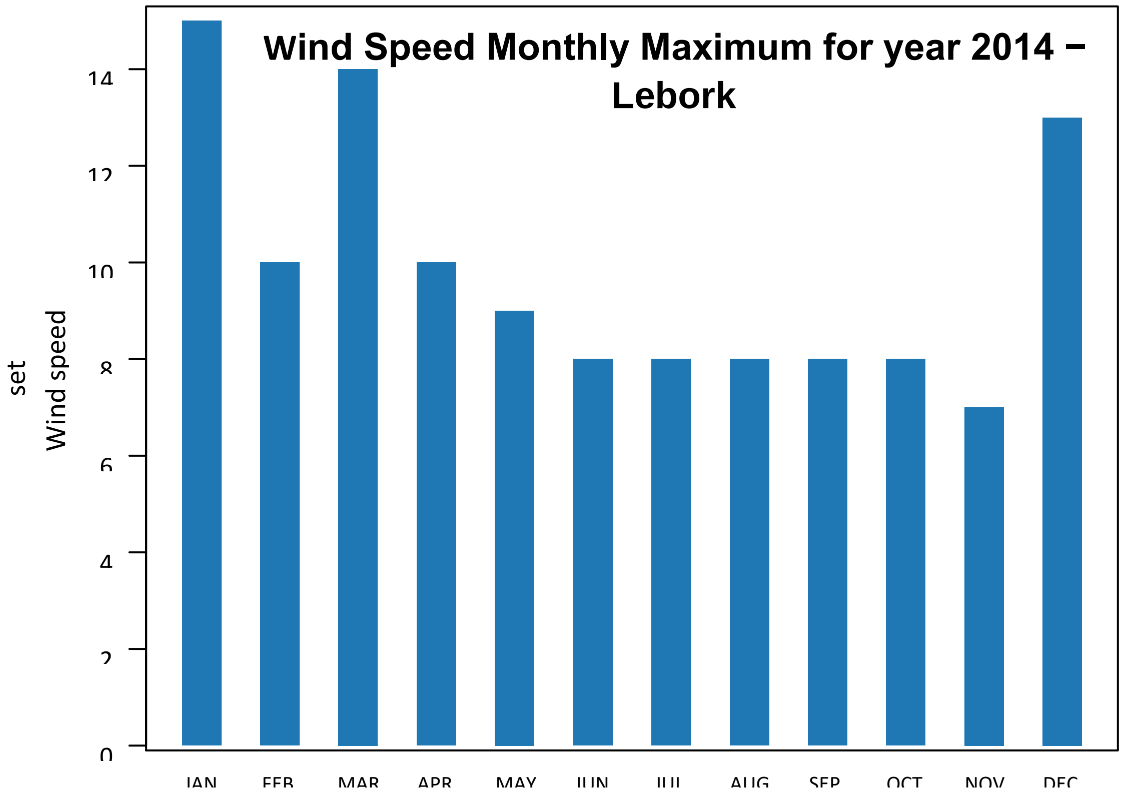


Figure 23: Monthly maximum of wind speed in Lebork Meteo Station

Figure 22 and 23 depicts the monthly minimum and maximum values of wind speed respectively. Obviously, for all the months the lowest recorded wind speed value is 1m/s. Meanwhile different maximum values were recorded for each month. For January, March and December, the highest recorded wind speed is 15, 14, and 13m/s respectively. These three months have the highest recorded values amongst all the months. All other months have slightly varied high values. For instance, February and April has 10m/s, may has 9m/s, June, July, August, September, and October has 8m/s as the highest value of windspeed – the reason for the uniformity in these four months could possibly be because the months are generally relatively warmer than the other months. The lowest maximum value of wind speed was recorded in November with 7m/s. The breakdown of the monthly statistics in depicted in Table 2.

D) Monthly Median

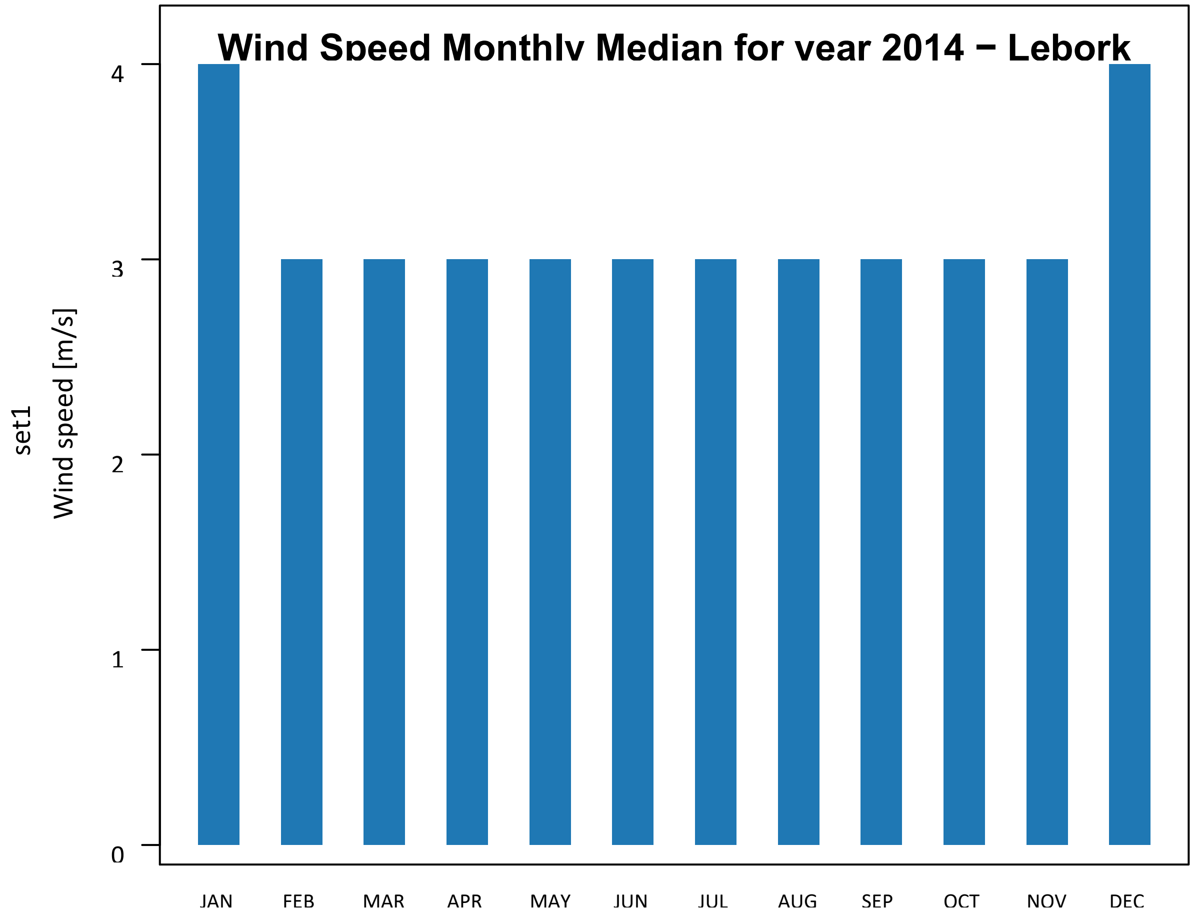


Figure 24: Monthly median of wind speed in Lebork Meteo Station

Median is a point denoting or relating to a value or quantity lying at the midpoint of a frequency distribution of observed values or quantities, such that there is an equal probability of falling above or below it. As such, Figure 24 reveals that at Lebork, the monthly median value for wind speed is relatively equal for all the months with a value of 3m/s. the only deviation occurs in the months of January and December both having 4m/s as median.

3.3.1 Diurnal Variation of Wind Speed

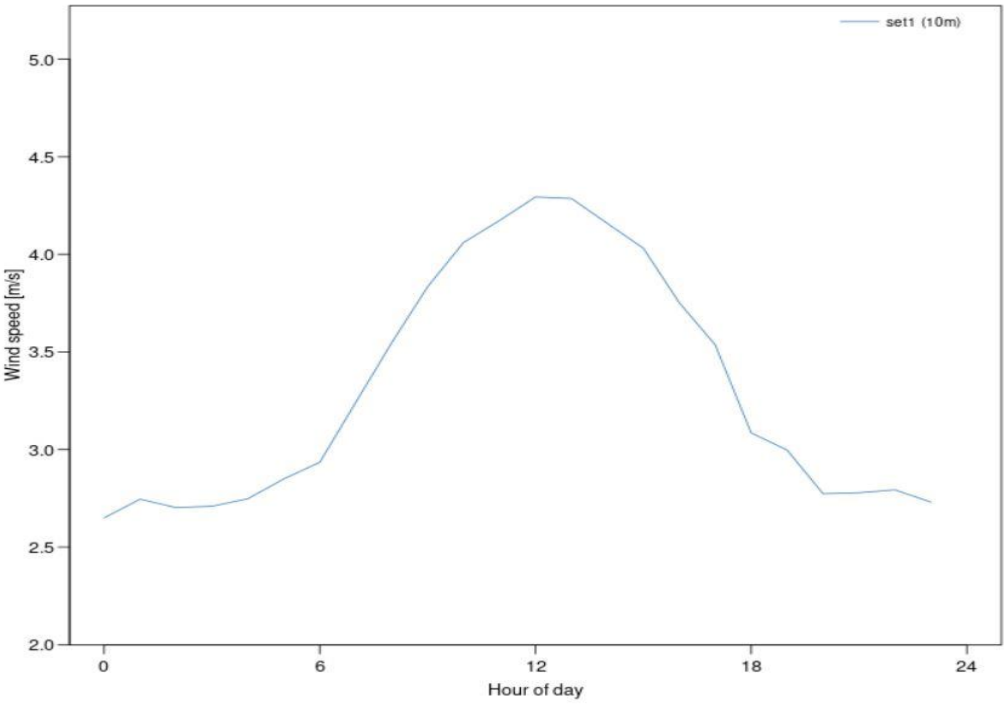


Figure 25: Diurnal Variation of Wind Speed in Lebork Meteo Station

3.3.2 Diurnal Variation of Wind Direction

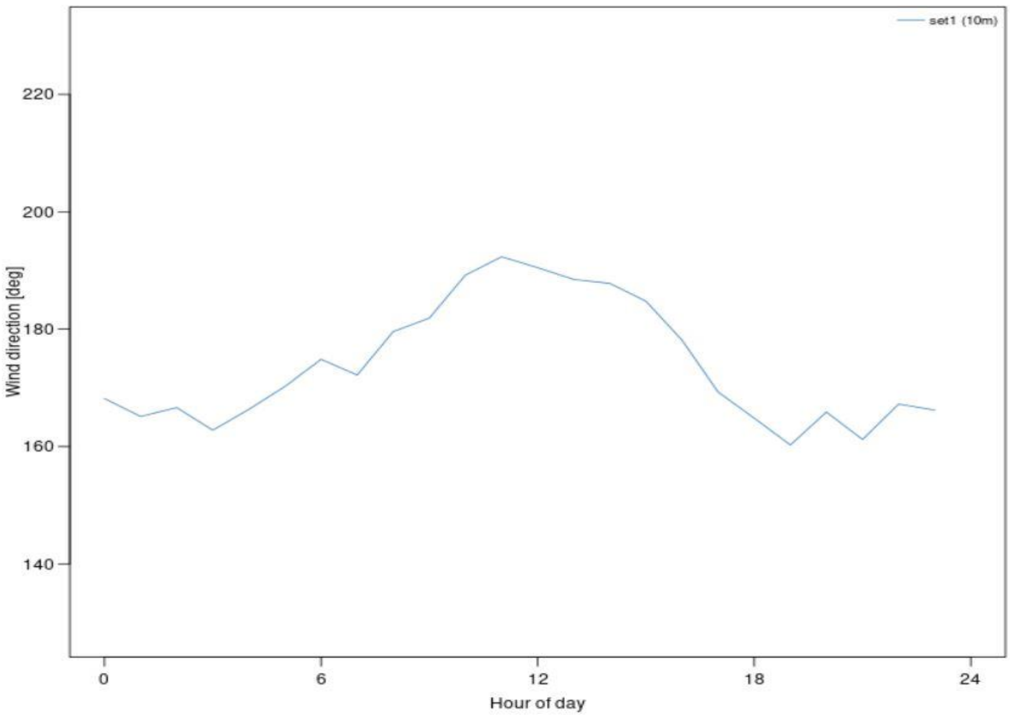


Figure 26: Diurnal Variation of Wind Direction in Lebork Meteo Station

Diurnal mean wind speed is depicted in Figure 25. The Figure shows hours of day that has a suitable wind speed in all over the year. The Figure shows that the wind speed in the study area follows a normal distribution pattern, and it is strongly influenced by the hours of the day, has hours with sufficient day light seems to have higher wind speed values. Best wind speeds almost occur at around 6 am to 6pm, specifically peaking at 12pm (mid-day). Poor wind speeds almost occur at around 12am – 6 am and 6pm – 12am when the day is relatively calm. Figure 26 reveals the diurnal variation of wind direction in the study area. Like the wind speed, the wind direction varies throughout the hours of the day. Specifically, between the hours of 6am to 6pm, having higher direction (degrees), essentially like the wind speed. Other periods of the day relatively witness lesser wind direction. The inference that can be drawn from this is that the wind direction and speed are essentially influenced by daylights, and by one another.

Table2: Summary of Monthly Wind Speed Statistics

Months	Mean	Standard Deviation	Median	Maximum	Minimum
January	4.533	2.009	4	15	1
February	3.508	1.533	3	10	1
March	3.755	2.518	3	14	1
April	3.231	1.770	3	10	1
May	3.144	1.723	3	9	1
June	2.869	1.593	3	8	1
July	2.996	1.709	3	8	1
August	3.205	1.673	3	8	1
September	2.813	1.435	3	8	1
October	2.819	1.511	3	8	1
November	2.743	1.359	3	7	1
December	4.102	2.230	4	13	1
	3.323 (Mean)	**1.878 (SD)**	**3 (Median)**	**15 (Maximum)**	**1 (Minimum)**
	3.310 (Mean of Months)		**3 (Median of month)**		

Source: Sulakshi & Rowland's Work, 2022

3.4 Calculating and Plotting a Wind Rose Plot

Wind rose is a diagram that summarizes information about the frequency and direction of wind at a particular location over a specified period (Encylopaedia Britannica, 2022). It is a tool for displaying the direction of the wind for siting analysis. As such, this section presents the analysis of the win direction at Lebork meteorological station using wind rose plots. First, as shown in Table 3 and Figure 27 attempt was made to calculate the frequency of occurrence using 12 wind direction sectors, separated into four bins – which is the default. Thereafter, attempts were made to plot the wind speed data in 8 and 16 sectors with four bins as depicted in Figures 28, 29 and 30. And Finally wind distribution for 12 sectors were calculated using fifteen bins as shown in Figures 31 and 32.

Table 3: The Frequency of Occurrence and Mean Wind Speed per Wind Direction Sector

Direction Sector	Wind Speed [m/s]	Total [%]	0-5 [%]	5-10 [%]	10-15 [%]	Greater than 15
N	2.635	2.541	2.345	0.195		
NME	3.045	3.237	2.504	0.733		
ENE	3.523	10.188	7.33	2.859		
E	2.897	12.13	10.347	1.784		
ESE	2.848	12.705	10.176	2.529		
SSE	2.878	10.09	8.515	1.576		
S	3.239	7.415	5.949	1.466		
SSW	3.41	9.125	7.122	2.003		
WSW	3.646	14.036	10.115	3.836	0.086	
W	4.357	10.445	5.803	4.141	0.489	0.012
WNW	3.768	4.838	3.225	1.515	0.098	
NNW	2.906	3.249	2.797	0.452		
All	**3.323**	**100**	**76.228**	**23.088**	**0.672**	**0.012**

Source: Sulakshi & Rowland's Work, 2022

From Figure 27 and Table 3, it is obvious that the strongest winds are within the West and West South-West (WSW) sectors respectively claiming 10.445% and 14.036% of the entire winds in the study area. Although it appears that mostly the bulk of the winds are within the Southeast region. Using the WSW and W sectors in Table 3 and Figure 27 as basis for discussion, it is obvious that winds between 0-5 m/s accounts for 10.115%, 5-10 m/s accounts for 3.836% and winds between 10-15m/s accounts for 0.086% of the entire 14.036% of the winds that occurred in the WSW sector in the study area. Similarly, the West sector (W) accounted for 10.445% of the entire wind in the study area. Out of this, 0-5 m/s claimed 5.803%, 5-10m/s claimed 4.141%, 10-15m/s accounted for 0.489%, while winds greater than 15m/s accounted for 0.0012%. Generally, the frequency of occurrence of windspeed varies across sectors, and influenced by the number of bin division in the study area. Nevertheless, it is apparent that poor winds occur mostly in the north as majority of the winds in the region are within 0 -5 m/s and 5 – 10m/s with 2.345% and 0.195% respectively. Figures 28 to 32 reveals the break-down of the frequency of occurrence and mean wind speed in the study area with different sector division and bins.

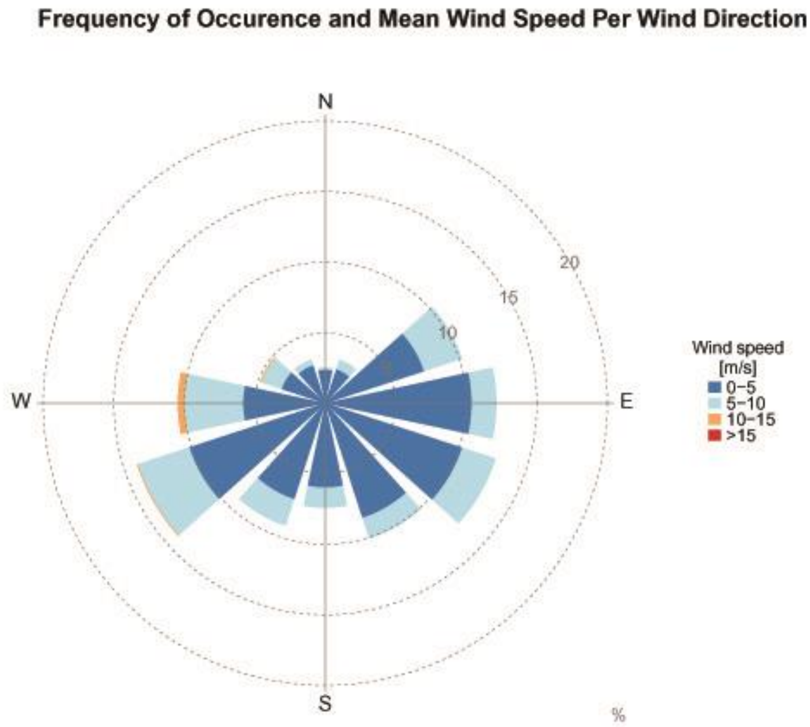


Figure 27: Frequency of occurrence and mean wind speed per direction (12 sectors with 4 bins)

```
> freq8
```

Frequency

	wind speed [m/s]	total [%]	0–5 [%]	5–10 [%]	10–15 [%]	>15 [%]
N	2.63	4.361	3.97	0.391		
NE	3.539	8.063	5.583	2.48		
E	3.038	21.219	17.139	4.08		
SE	2.731	15.05	12.912	2.138		
S	3.273	13.804	10.897	2.907		
SW	3.432	14.403	11.068	3.335		
W	4.149	17.64	10.616	6.389	0.623	0.012
NW	3.465	5.461	4.043	1.368	0.049	
all	3.323	100	76.228	23.088	0.672	0.012

```
> freq16
```

Frequency

	wind speed [m/s]	total [%]	0–5 [%]	5–10 [%]	10–15 [%]	>15 [%]
N	2.635	2.541	2.345	0.195		
NNE	2.82	2.04	1.698	0.342		
NE	3.492	2.883	2.016	0.867		
ENE	3.52	8.502	6.12	2.382		
E	2.897	12.13	10.347	1.784		
ESE	2.905	8.857	6.975	1.881		
SE	2.783	7.134	6.01	1.124		
SSE	2.887	6.804	5.705	1.099		
S	3.239	7.415	5.949	1.466		
SSW	3.462	6.474	4.984	1.49		
SW	3.356	5.803	4.532	1.27		
WSW	3.712	10.884	7.72	3.078	0.086	
W	4.357	10.445	5.803	4.141	0.489	0.012
WNW	3.814	3.482	2.309	1.075	0.098	
NW	3.406	2.651	1.942	0.709		
NNW	2.744	1.955	1.771	0.183		
all	3.323	100	76.228	23.088	0.672	0.012

Figure 28a and 28b: Break Down of Frequency of occurrence and mean wind speed per direction (for 8 and 16 sectors with 4 bins)

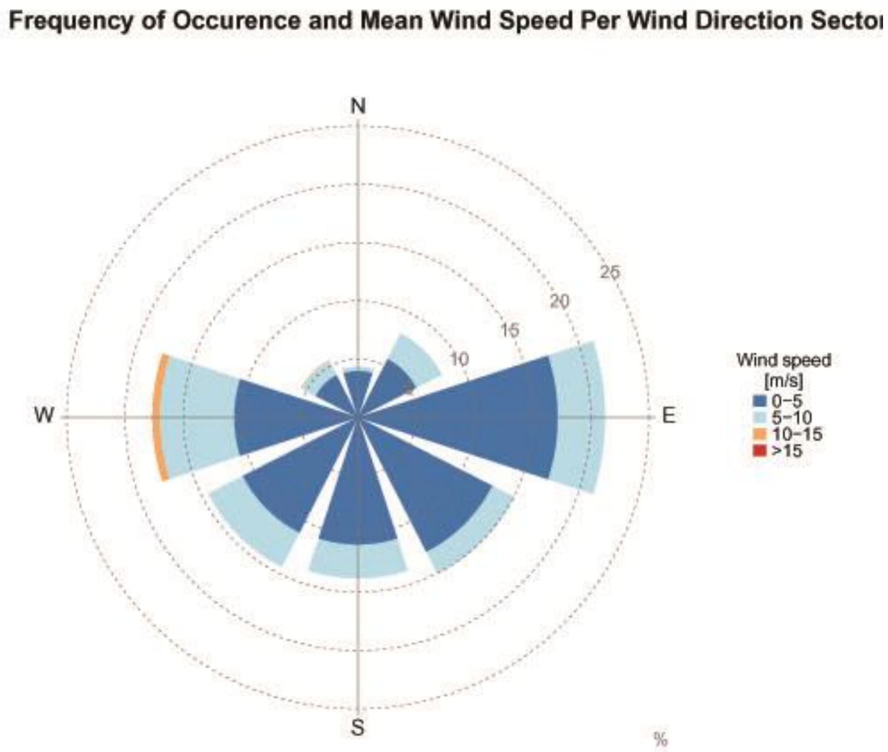


Figure 29: Frequency of occurrence and mean wind speed per direction(8 sectors with 4 bins)

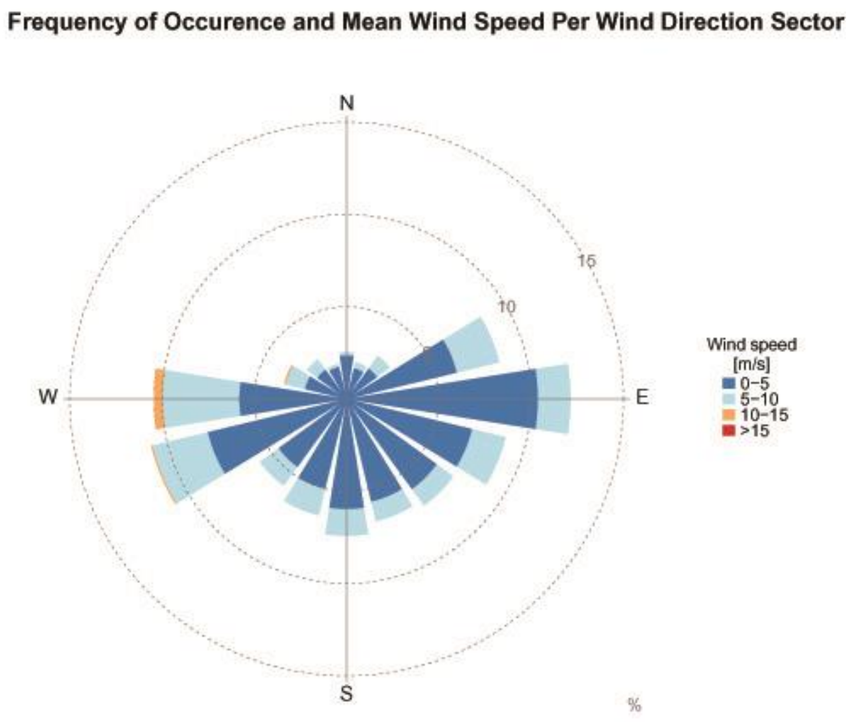


Figure 30: Frequency of occurrence and mean wind speed per direction (16 sectors with 4 bins)

```
>
> freqbincorrect=frequency(mast=metmastclean, v.set=1, bins=seq(1.5,15.5,1.0))#3
.7 changing wind speed

        Frequency

    wind speed  total  0-1.5 1.5-2.5 2.5-3.5 3.5-4.5 4.5-5.5 5.5-6.5 6.5-7.5
         [m/s]    [%]    [%]     [%]     [%]     [%]     [%]     [%]     [%]
N        2.635  2.541  0.586   0.586   0.757   0.415   0.171   0.024
NNE      3.045  3.237  0.806   0.709   0.574   0.415   0.354   0.208   0.147
ENE      3.523 10.188  1.063   2.248   2.052   1.967   1.417   0.941   0.428
E        2.897  12.13  2.455   3.054   2.797    2.04   1.002   0.501   0.232
ESE      2.848 12.705   3.14    3.64   1.784   1.613   1.466   0.818   0.232
SSE      2.878  10.09  2.419   1.942   2.407   1.747   1.075   0.391   0.073
S        3.239  7.415  1.209   1.405   1.735     1.6   0.782   0.452   0.147
SSW       3.41  9.125  1.038   1.441   2.284   2.358   1.393   0.428   0.086
WSW      3.646 14.036  1.319   2.944   3.384   2.468   1.747   0.989   0.599
W        4.357 10.445   1.82   1.564   1.319   1.099    1.27   1.075   1.026
WNW      3.768  4.838  0.733   0.818   0.941   0.733   0.709    0.44   0.171
NNW      2.906  3.249  0.684   0.672   0.733   0.709   0.354   0.073   0.024
all      3.323    100 17.273  21.024  20.767  17.163   11.74    6.34   3.164
    7.5-8.5 8.5-9.5 9.5-10.5 10.5-11.5 11.5-12.5 12.5-13.5 13.5-14.5 14.5-15.5
        [%]     [%]      [%]       [%]       [%]       [%]       [%]       [%]
N
NNE   0.012   0.012
ENE   0.073
E     0.049
ESE   0.012
SSE   0.037
S     0.024   0.061
SSW   0.098
WSW   0.342   0.159    0.037     0.037     0.012
W     0.379   0.391    0.171     0.134      0.11     0.049     0.024     0.012
WNW   0.147   0.049    0.024     0.037     0.024               0.012
NNW
all   1.173   0.672    0.232     0.208     0.147     0.049     0.037     0.012

call: frequency(mast=metmastclean, v.set=1, dir.set=1, num.sectors=12, bins=c(0,
 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, 9.5, 10.5, 11.5, 12.5, 13.5, 14.5, 15.5
), subset=NA, digits=3, print=TRUE)
```

Figure 31: Frequency of occurrence and mean wind speed per direction (12 sectors with 15 bins)

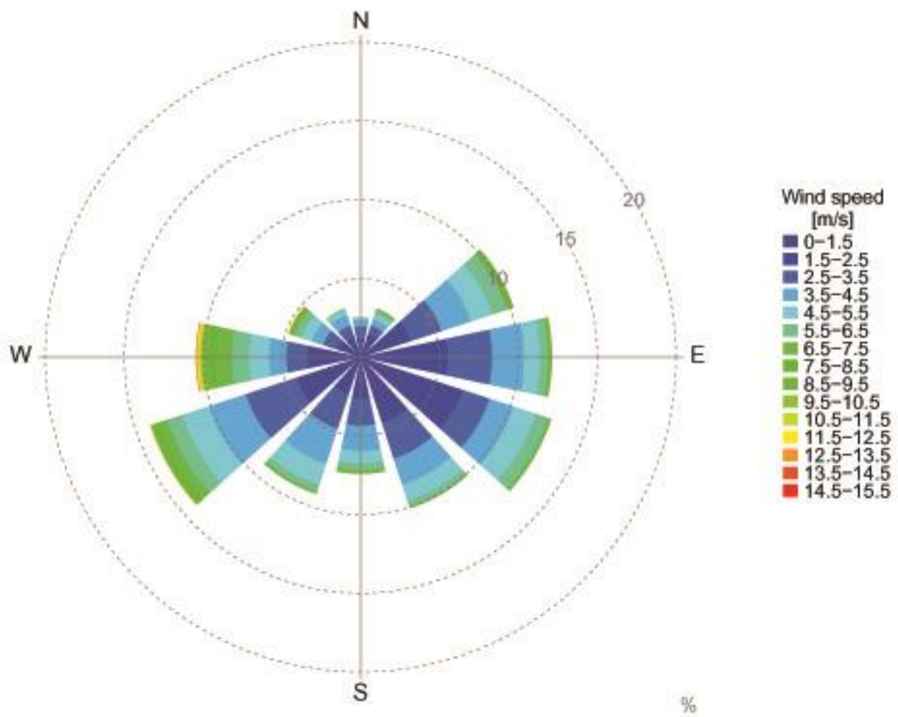


Figure 32: Frequency of occurrence and mean wind speed per direction (12 sectors with 15 bins)

3.5 Calculating Weibull Parameters and Plotting Weibull Distribution

The Weibull distribution is a continuous probability distribution that can fit an extensive range of distribution shapes. Like the normal distribution, the Weibull distribution describes the probabilities associated with continuous data (Jim, 2021). As such, this section presents the results of the fitted Weibull distribution with the wind speed and wind direction data for eight sectors. The result depicted in Table 4 shows the values of the calculated Weibull parameters – that is, shape (K) and scale (A), with the corresponding wind speed and frequency. The result of the distribution of wind speed and the Weibull distribution depicted in Figure 33 clearly shows that the Weibull perfectly fits the actual data well.

Table 4: Weibull Parameters and Plotting Weibull distribution

Direction Sector	A (Scale) [m/s]	K (Shape)	Wind Speed [m/s]	Frequency [%]
N	2.97	2.201	2.63	4.361
NE	3.995	2.053	3.539	8.063
E	3.428	1.987	3.038	21.219
SE	3.078	1.904	2.731	15.05
S	3.695	2.16	3.273	13.804
SW	3.875	2.244	3.432	14.403
W	4.64	1.652	4.149	17.64
NW	3.907	1.926	3.465	5.461
All	**3.736**	**1.796**	**3.323**	**100**

Source: Sulakshi & Rowland's Work, 2022

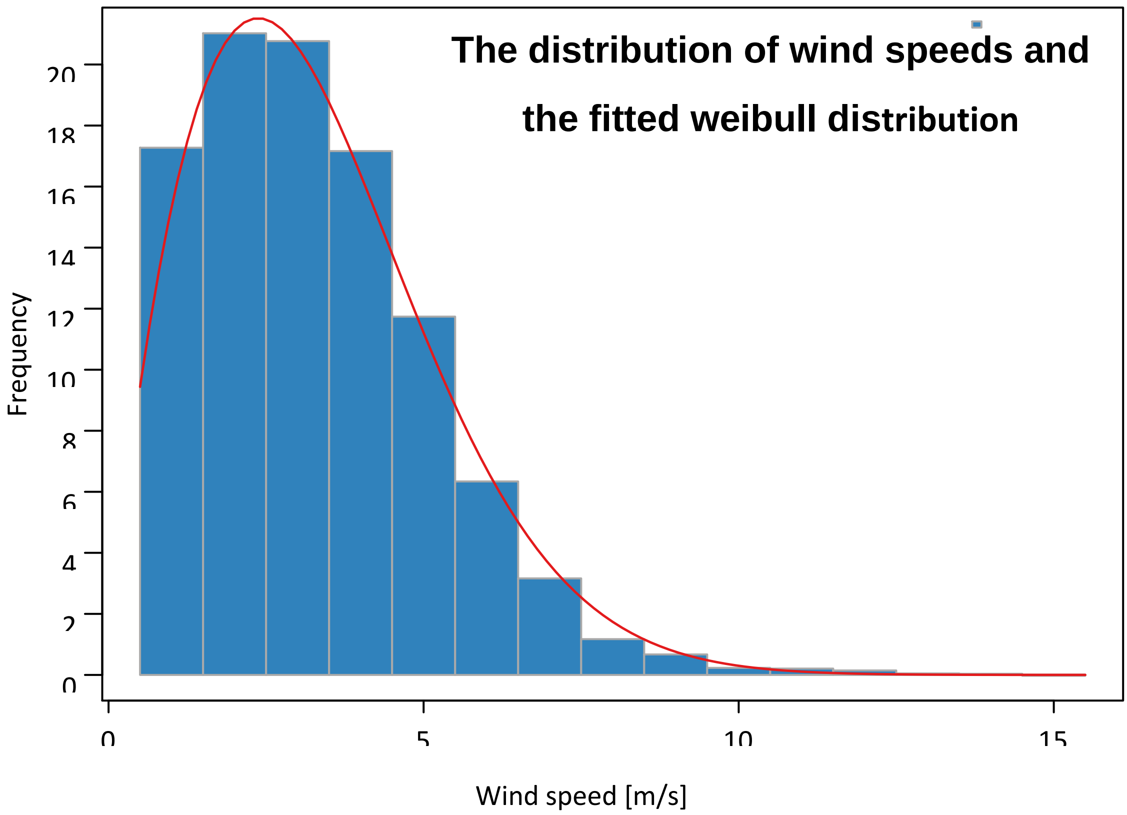


Figure 33: The distribution of wind speeds and the fitted weibull distribution

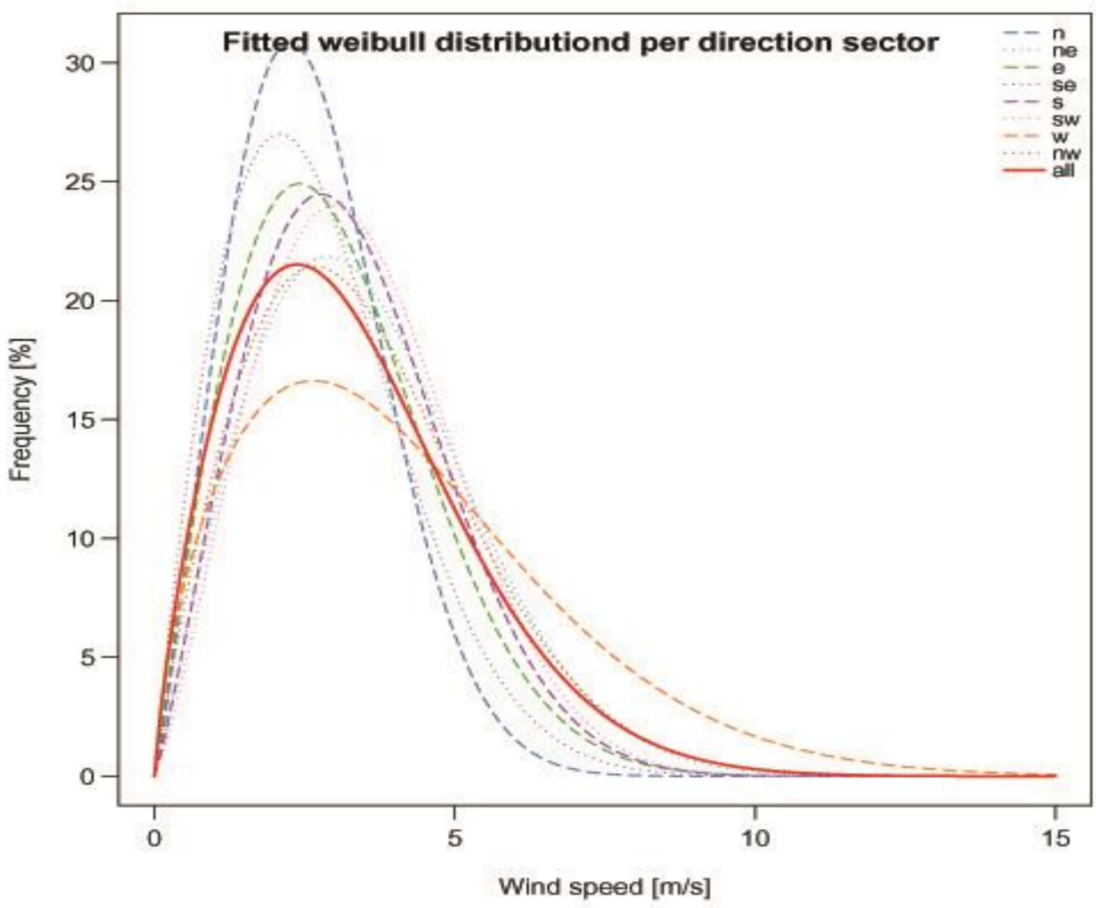


Figure 34: Fited weibull distribution per direction sector

Figure 34 reveals the Weibull distribution per direction sector. A comparison of the theoretical statistical distribution reveals by the Weibull and the actual data in Wind rose in Figure 28a, 29 and Table 3 shows that in all the sectors 0-5 m/s is the most frequently observed wind speed in all directions, and with the average wind speed slightly varying between 2.5 and 3.5m/s.

3.6 Calculating and Plotting Total Wind Energy Content

In wind resource assessment one of the most important parameters is the wind energy. Hence this section deals with the calculation of the wind energy content per direction sector from Weibull data. To achieve this, first the mean air pressures and the mean temperature were determined in pascals and kelvin.

Mean air pressure (P) = 101011.8pa

Mean air temperature (T) = 101011.8K

Specific gas constant ($R_{specific}$)= 287 J/kg.K

Thereafter, the mean annual air density for Lebork was calculated from the ideal gas law.

$$Rho = P/R_{specific} * T$$

$$Rho = 101011.8/287 * 101011.8$$

$$\text{Mean annual air density} \approx 1.2452\ kg/m^3$$

This was used to calculate the total wind energy content per direction sector from Weibull data. The results are therefore presented in Figure 35 and Tables 5a and 5b.

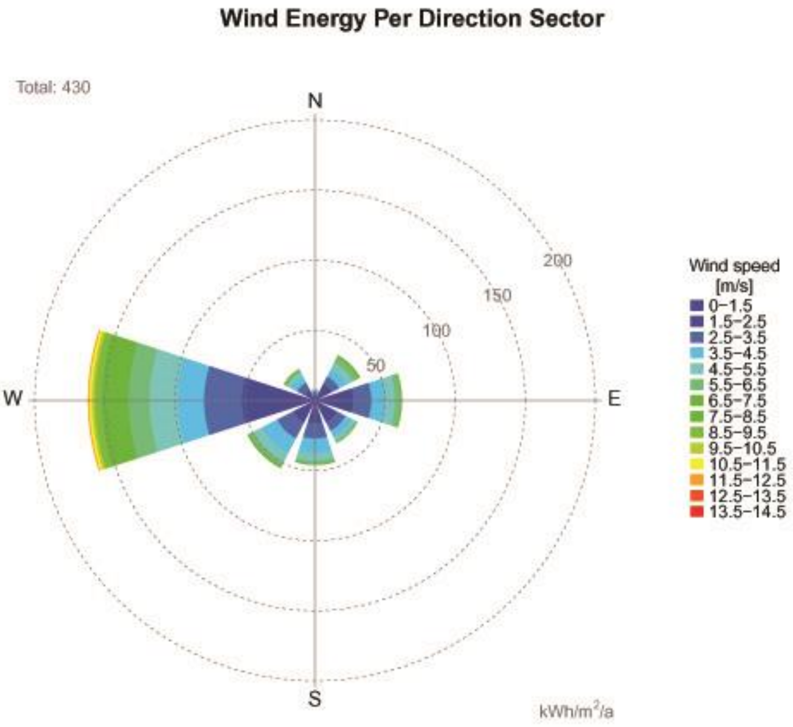


Figure 35: Wind Energy Per Direction Sector

Table 5a: Total Wind Energy Per Direction Sector

Direction Sector	Total	0-1.5 [KWh/m²/a]	1.5-2.5 [KWh/m²/a]	2.5-3.5 [KWh/m²/a]	3.5-4.5 [KWh/m²/a]	4.5-5.5 [KWh/m²/a]	5.5-6.5 [KWh/m²/a]	6.5-7.5 [KWh/m²/a]	7.5-8.5 [KWh/m²/a]
N	8	2	2	2	1	1			
NE	36	6	7	6	6	5	4	2	
E	62	12	15	13	10	8	4	1	
SE	34	8	9	7	5	3	2		
S	47	8	8	11	10	6	2	1	
SW	55	6	11	13	12	7	3	1	1
W	163	24	28	27	19	20	15	13	6
NW	25	4	4	6	5	3	2	1	
All	**430**	**70**	**84**	**85**	**68**	**52**	**32**	**19**	**7**

Source: Sulakshi & Rowland's Work, 2022

Table 5b: Continued - Total Wind Energy Per Direction Sector

Direction Sector	8.5-9.5 [KWh/m²/a]	9.5-10.5 [KWh/m²/a]	10.5-11.5 [KWh/m²/a]	11.5-12.5 [KWh/m²/a]	12.5-13.5 [KWh/m²/a]	13.5-14.5 [KWh/m²/a]
N						
NE						
E						
SE						
S						
SW						
W	5	2	2	1	-	-
NW						
All	**5**	**2**	**2**	**1**	**-**	**-**

Source: Sulakshi & Rowland's Work, 2022

Tables 5a and 5b reveals the total wind energy (including the break down into fourteen bins) per wind direction sector in the study area. The energy plot depicted in the wind rose in Figure 35 also clearly validates the results in Table 5a and 5b. As seen in the Tables and Figure, the Highest wind energy is recorded in the West direction with 163 [KWh/m2/a], followed by the East direction with 62 [KWh/m2/a]. Next to these is the Southwest and the South directions with 55 and 47 [KWh/m2/a] respectively. This result essentially validates the result earlier affirmed in section 3.4 with Figure 27, 28, 29 and 32.

3.7 The Wind Speed at Hub Height – Wind Profiles at 10 meters

This section deals with the wind profiles using the alpha value of 0.22 with the Hellman exponential law defined as.

$$\frac{V_1}{V_2} = \left(\frac{h_2}{h_1}\right)^{\alpha}$$

Where V_2 is the wind speed at height h_2, V_1 is the wind speed at height h_1 and α is the Hellman exponent (also power law exponent or shear exponent).

Meanwhile, α depends on various issues, including roughness and terrain of the site. Therefore, to estimate α, careful observation of the site's terrain using google earth imagery revealed the site belongs to the "flat terrain, open land cover" group specified in the bReeze manual. Hence the corresponding upper limit of value (which is 0.22) specified for such terrain was selected. The extrapolated wind speeds by wind profile in therefore presented in Table 6, while the wind profile per direction sector is depicted in Figure 36.

Table 6: Continued - Total Wind Energy Per Direction Sector

Direction Sector	Alpha value	Wind Speed [m/s]
N	0.22	2.63
NE	0.22	3.539
E	0.22	3.038
SE	0.22	2.731
S	0.22	3.273
SW	0.22	3.432
W	0.22	4.149
NW	0.22	3.465
All	0.22	**3.323**

Source: Sulakshi & Rowland's Work, 2022

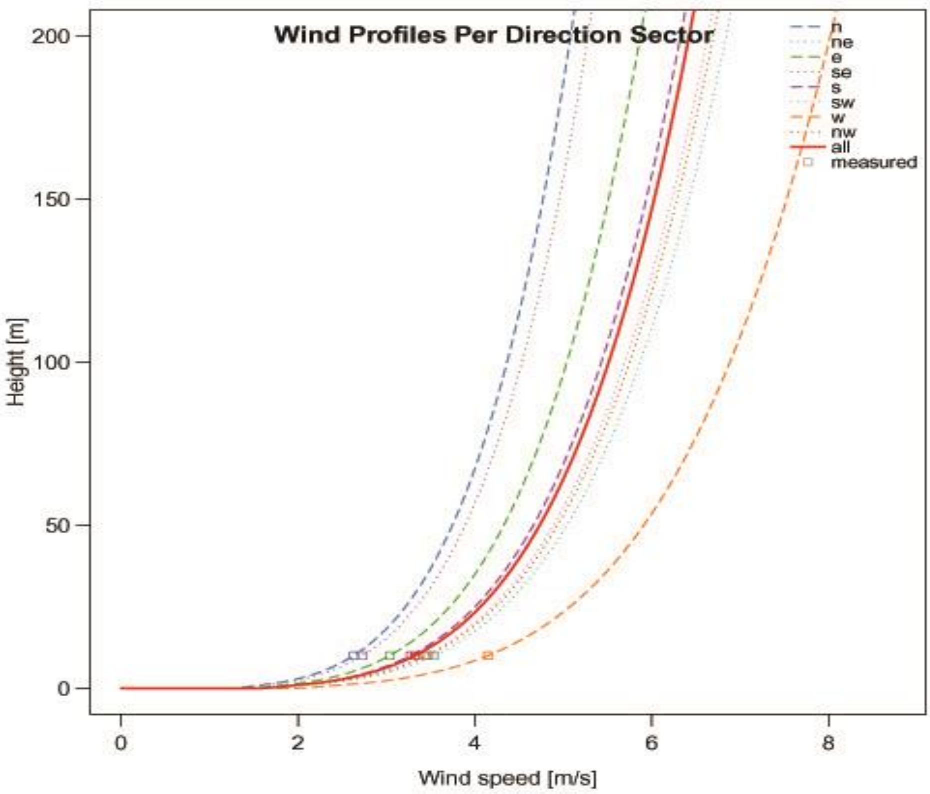


Figure 36: Wind Profiles Per Direction Sector

A wind turbine's hub height is the distance from the ground to the middle of the turbine's rotor (US Department of Energy, 2021). Figure 36 validates the wind speed specified in Table 6 at height of 10meters. In addition, it further reveals the extrapolated wind speeds at various hub heights up to 200m. Virtually at the at the height of 100m for all direction sector, more than 4m/s wind speed will be generated. The wind speed likely to be generated increases with increased height. Hence, this result validates the several claims made by researchers that the bigger the turbines, the better the energy likely to be generated.

3.8 Lebork's Energy Production with Turbines

Wind energy is the amount of kinetic power (mechanical or electrical) likely to be generated by wind turbines. As such this section estimates the energy that will be generated from wind turbines installed in Lebork meteorological station. First a comparison was made between two types of turbines (Vestas and Nordex) shown in Figures 37 and 38 respectively, by plotting their power curve. The breakdown of their power curves in Figure 39a and 39b revealed that Vestas has more rated capacity 3000KW than Nordex' 2500KW. In addition, at 15m/s (which is the highest recorded wind speed in Lebork) 2976KW power is generated from Vestas turbine, while 2500KW is generated from Nordex at the same wind speed. From figures 39a and 3b, a synthesis of the characteristics of the two wind turbines were made and presented in Table 7.

3.8.1 Comparing Power Curves of Two Wind turbines – Vestas and Nordex

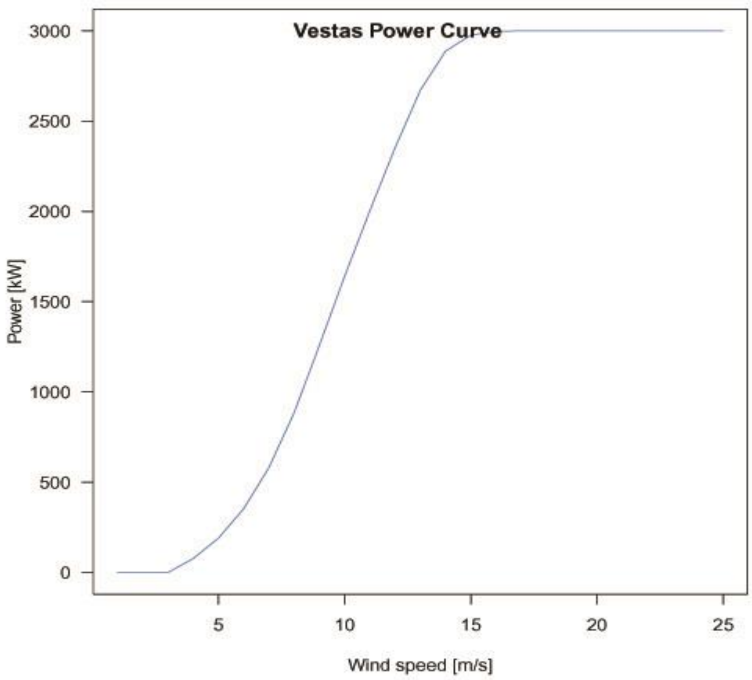


Figure 37: Power Curve of Vestas Wind Turbine

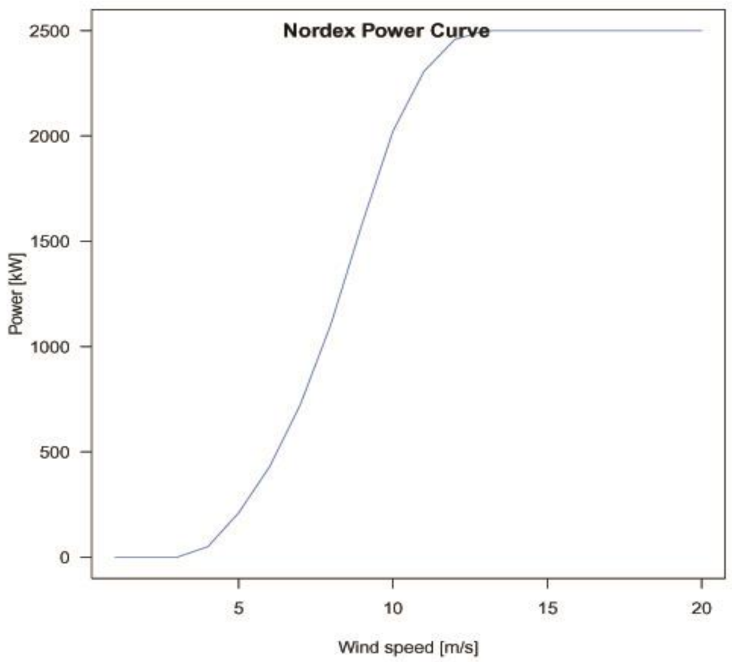


Figure 38: Power Curve of Nordex Wind Turbine

```
> vestas

        Power curve

description: Vesta V90 3mW 106.7dB(A)
rated power: 3000
air pressure: 1.225

   wind speed power
        [m/s]   [kW]
1           1      0
2           2      0
3           3      0
4           4     77
5           5    190
6           6    353
7           7    581
8           8    885
9           9   1258
10         10   1641
11         11   2004
12         12   2353
13         13   2671
14         14   2888
15         15   2976
16         16   2997
17         17   3000
18         18   3000
19         19   3000
20         20   3000
21         21   3000
22         22   3000
23         23   3000
24         24   3000
25         25   3000
```

```
> Nordex

        Power curve

description: Nordex N100 2500kw
rated power: 2500
air pressure: 1.225

   wind speed power
        [m/s]   [kW]
1           1      0
2           2      0
3           3      0
4           4     50
5           5    211
6           6    429
7           7    725
8           8   1111
9           9   1583
10         10   2023
11         11   2306
12         12   2458
13         13   2500
14         14   2500
15         15   2500
16         16   2500
17         17   2500
18         18   2500
19         19   2500
20         20   2500
```

Figure 39a and 39b: Break Down of Power Curve of Nordex Wind Turbine

Table 7: Synthesised Characteristics of Vestas and Nordex Wind Turbines – a comparison

Wind Turbine Type	Rated Capacity [KW]	Minimum Velocity (Velocity needed to generate power [m/s])	Power Generated (from minimum velocity)	Power produced at 15m/s (Highest wind speed in Lebork	Velocity Rated (Velocity needed to generate Rated capacity [m/s])	Velocity Cut-off [m/s]
Vestas_V90_3.0MW	3000	4	77	2976	17	25
Nordex_N100_2.5MW	2500	4	50	2500	13	20

Source: Sulakshi & Rowland's Work, 2022

3.8.2 Calculating Energy Production for Vestas and Nordex Wind Turbines

A) Energy Production for Vestas Wind Turbine at 80m

The energy production using vestas wind turbine was calculated for 80m and 100m heights. The results depicted in Figure 40 entirely agrees with the one depicted in Figure 41. They both reveal the amount of energy generated at 80m. Figure 41 and 42 reveals that at 80m, the total energy generated is 3827 [MWh/a]. The amongst the eight sectors, the West sector accounts for the highest energy generated with 1192 [MWh/a], while the North sector also accounts for the lowest energy generated with 74 [MWh/a].

Annual energy production

	wind speed [m/s]	operation [h/a]	total [MWh/a]	0-4.5 [MWh/a]	4.5-5.5 [MWh/a]	5.5-6.5 [MWh/a]	6.5-7.5 [MWh/a]	7.5-8.5 [MWh/a]
N	4.156	382	74	2	12	16	15	12
NE	5.593	706	352	3	19	32	44	52
E	4.8	1859	621	9	52	79	98	103
SE	4.316	1318	333	7	36	50	57	55
S	5.171	1209	471	6	35	57	74	81
SW	5.422	1262	550	6	37	62	84	94
W	6.556	1545	1192	5	31	53	79	104
NW	5.475	478	234	2	12	20	28	33
total	5.25	8760	3827	40	234	369	479	534

	8.5-9.5 [MWh/a]	9.5-10.5 [MWh/a]	10.5-11.5 [MWh/a]	11.5-12.5 [MWh/a]	12.5-13.5 [MWh/a]	13.5-14.5 [MWh/a]	14.5-15.5 [MWh/a]
N	8	4	1				
NE	54	48	37	26	16	9	5
E	93	71	47	28	15	7	3
SE	46	32	19	10	5	2	1
S	74	57	37	22	11	5	2
SW	89	70	47	28	14	6	2
W	125	134	131	120	104	85	64
NW	34	31	25	18	12	7	4
total	523	447	344	252	177	121	81

	15.5-16.5 [MWh/a]	16.5-17.5 [MWh/a]	17.5-18.5 [MWh/a]	18.5-19.5 [MWh/a]	19.5-20.5 [MWh/a]	>20.5 [MWh/a]
N						
NE	2	1				
E	1					
SE						
S	1					
SW	1					
W	47	33	23	16	11	17
NW	2	1				
total	54	35	23	16	11	17

capacity factor: 0.146

Figure 40: Breakdown of Engergy Production with Vestas Wind Turbine at 80m

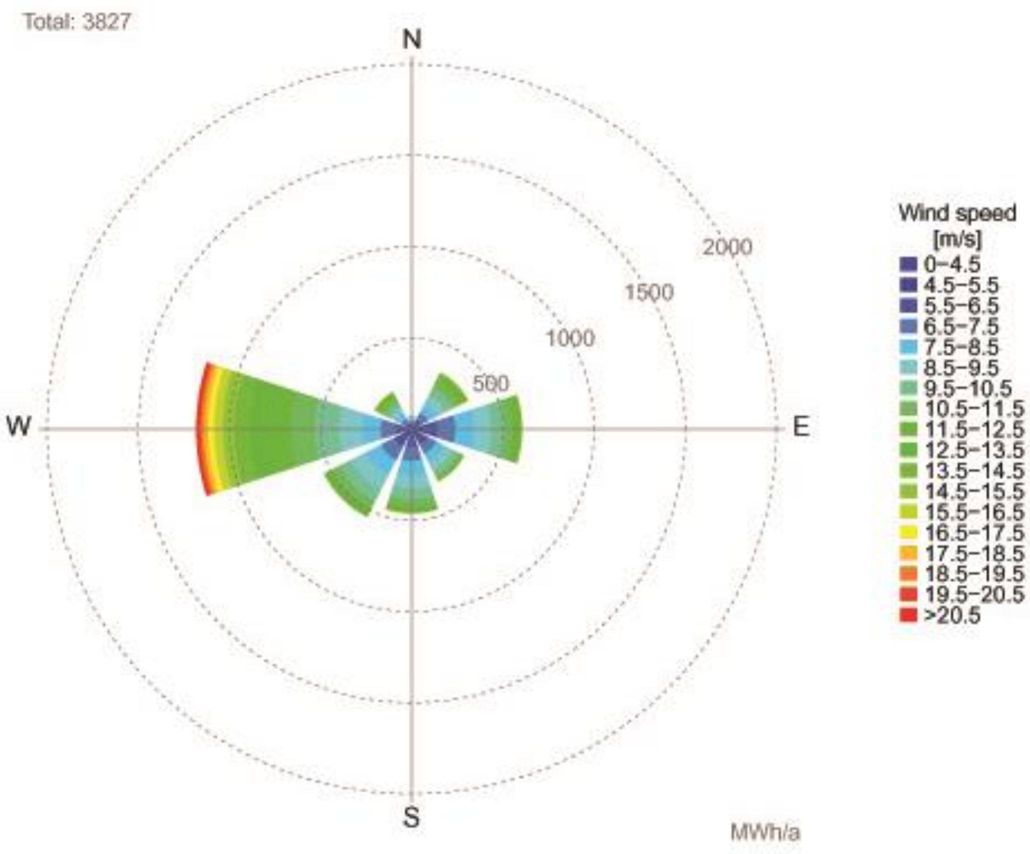


Figure 41: Engergy Production with Vestas Wind Turbine at 80m

B) Energy Production for Vestas Wind Turbine at 105m

Figure 42 and 43 reveals the effects of the increased height of turbine on the energy generated. At 105, the total energy generated increased to 4443 [MWh/a]. The West direction sector still accounts for the highest energy generated with 1333 [MWh/a], while the North sector also still accounts for the lowest energy generated with 790 [MWh/a]. This clearly reveals that at the same wind speed, higher turbines height generates more energy than lower turbines height.

Annual energy production

	wind speed [m/s]	operation [h/a]	total [MWh/a]	0-4.5 [MWh/a]	4.5-5.5 [MWh/a]	5.5-6.5 [MWh/a]	6.5-7.5 [MWh/a]	7.5-8.5 [MWh/a]
N	4.412	382	90	2	12	17	18	16
NE	5.937	706	410	3	18	31	45	56
E	5.096	1859	736	9	51	81	105	116
SE	4.582	1318	398	7	36	53	63	65
S	5.49	1209	557	5	34	57	78	90
SW	5.757	1262	648	5	35	61	87	103
W	6.96	1545	1333	5	29	52	78	105
NW	5.813	478	271	2	12	20	28	35
total	5.574	8760	4443	38	227	372	502	586

	8.5-9.5 [MWh/a]	9.5-10.5 [MWh/a]	10.5-11.5 [MWh/a]	11.5-12.5 [MWh/a]	12.5-13.5 [MWh/a]	13.5-14.5 [MWh/a]	14.5-15.5 [MWh/a]
N	11	6	3	1			
NE	60	57	47	35	24	15	8
E	112	92	66	42	25	13	6
SE	58	44	29	17	9	4	2
S	89	74	53	34	19	10	4
SW	105	90	66	43	25	12	5
W	129	142	142	135	121	101	79
NW	38	36	31	24	17	11	7
total	602	541	437	331	240	166	111

	15.5-16.5 [MWh/a]	16.5-17.5 [MWh/a]	17.5-18.5 [MWh/a]	18.5-19.5 [MWh/a]	19.5-20.5 [MWh/a]	>20.5 [MWh/a]
N						
NE	4	2	1			
E	3	1				
SE	1					
S	2	1				
SW	2	1				
W	60	44	32	23	16	33
NW	4	2	1			
total	76	51	34	23	16	33

capacity factor: 0.169

Figure 42: Breakdown of Engergy Production with Vestas Wind Turbine at 105m

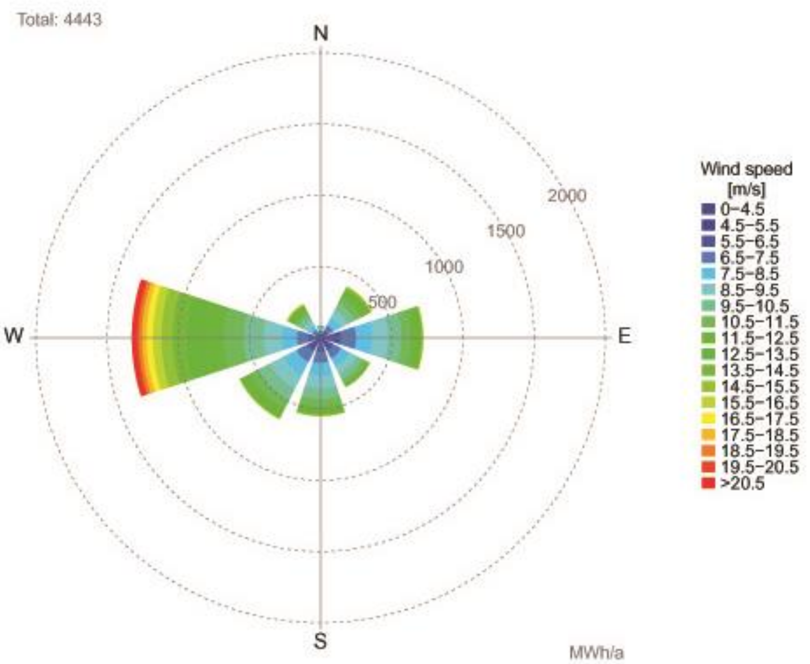


Figure 43: Engergy Production with Vestas Wind Turbine at 105m

C) Energy Production for Nordex Wind Turbine at 80m

Final estimation of the energy generated from the site using Nordex turbine was made. The results generated for 80m height is depicted in Figures 44 and 45, while that generated for 100m height is depicted in Figures 46 and 47 in section D. As depicted in Table 8, same pattern was observed in the two cases when compared to Vestas. The difference in the amount of energy generated for Nordex 80m hub height when compared that generated for Nordex 100m hub height is entirely due to the increased hub height. For 80m and 100m heights the total energy generated is 4384 [MWh/a] and 4931 [MWh/a] respectively. In addition, for 80m and 100m, the highest energy is generated from the West sector with 1284[MWh/a] and 1391 [MWh/a] respectively. While the lowest energy was also generated from the North sector with 87 [MWh/a] and 103 [MWh/a] for 80m and 100m respectively.

Annual energy production

	wind speed [m/s]	operation [h/a]	total [MWh/a]	0-4.5 [MWh/a]	4.5-5.5 [MWh/a]	5.5-6.5 [MWh/a]	6.5-7.5 [MWh/a]	7.5-8.5 [MWh/a]
N	4.156	382	87	1	13	19	19	15
NE	5.593	706	410	1	21	39	55	65
E	4.8	1859	732	4	58	97	123	129
SE	4.316	1318	391	3	40	61	72	69
S	5.171	1209	558	2	39	70	93	101
SW	5.422	1262	652	2	41	76	104	118
W	6.556	1545	1284	2	34	65	99	131
NW	5.475	478	270	1	14	25	35	41
total	5.25	8760	4384	16	260	452	600	669

	8.5-9.5 [MWh/a]	9.5-10.5 [MWh/a]	10.5-11.5 [MWh/a]	11.5-12.5 [MWh/a]	12.5-13.5 [MWh/a]	13.5-14.5 [MWh/a]	14.5-15.5 [MWh/a]
N	10	5	2	1			
NE	68	59	42	27	15	8	4
E	117	87	54	29	14	6	2
SE	57	39	22	11	5	2	1
S	93	70	43	23	10	4	2
SW	112	87	54	29	13	5	2
W	157	165	151	126	98	73	54
NW	43	38	28	19	11	6	3
total	657	550	396	265	166	104	68

	15.5-16.5 [MWh/a]	16.5-17.5 [MWh/a]	17.5-18.5 [MWh/a]	18.5-19.5 [MWh/a]	19.5-20.5 [MWh/a]	>20.5 [MWh/a]
N						
NE	2	1				
E	1					
SE						
S	1					
SW	1					
W	39	28	19	13	9	14
NW	2	1				
total	46	30	19	13	9	14

capacity factor: 0.2

Figure 44: Breakdown of Engergy Production with Nordex Wind Turbine at 80m

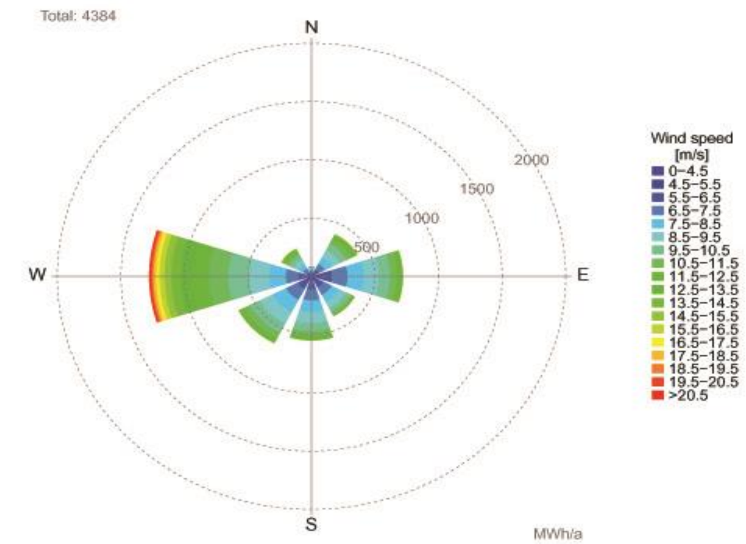


Figure 45: Engergy Production with Nordex Wind Turbine at 80m

D) Energy Production for Nordex Wind Turbine at 100m

```
> Leborkaep_n100 <- aep(profile=Leborkhub_height, pc=Nordex, hub.h=100,  bins=seq(4.5,20.5,1.0), rho=1.2452)

        Annual energy production

      wind speed operation   total   0-4.5 4.5-5.5 5.5-6.5 6.5-7.5 7.5-8.5
           [m/s]      [h/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a]
N          4.365        382     103       1      13      20      22      19
NE         5.874        706     461       1      20      38      56      69
E          5.042       1859     839       4      57      98     130     143
SE         4.533       1318     453       3      40      64      78      79
S          5.431       1209     638       2      38      70      97     111
SW         5.695       1262     743       2      39      75     108     128
W          6.885       1545    1391       2      33      63      98     132
NW         5.751        478     303       1      13      24      35      44
total      5.515       8760    4931      16     253     452     624     725
      8.5-9.5 9.5-10.5 10.5-11.5 11.5-12.5 12.5-13.5 13.5-14.5 14.5-15.5
      [MWh/a]  [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]
N          13        7         3         1
NE         75       68        52        35        21        12         6
E         136      108        72        41        21        10         4
SE         70       51        31        16         8         3         1
S         108       87        57        33        16         7         3
SW        128      106        72        41        21        10         4
W         162      173       162       138       110        85        64
NW         47       44        34        24        15         9         5
total     739      644       483       329       212       136        87
      15.5-16.5 16.5-17.5 17.5-18.5 18.5-19.5 19.5-20.5   >20.5
        [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a] [MWh/a]
N
NE            3         1         1
E             2         1
SE            1
S             1
SW            2         1
W            48        35        25        18        12      25
NW            3         1         1
total        60        39        27        18        12      25

capacity factor: 0.225
```

Figure 46: Breadown of Engergy Production with Nordex Wind Turbine at 100m

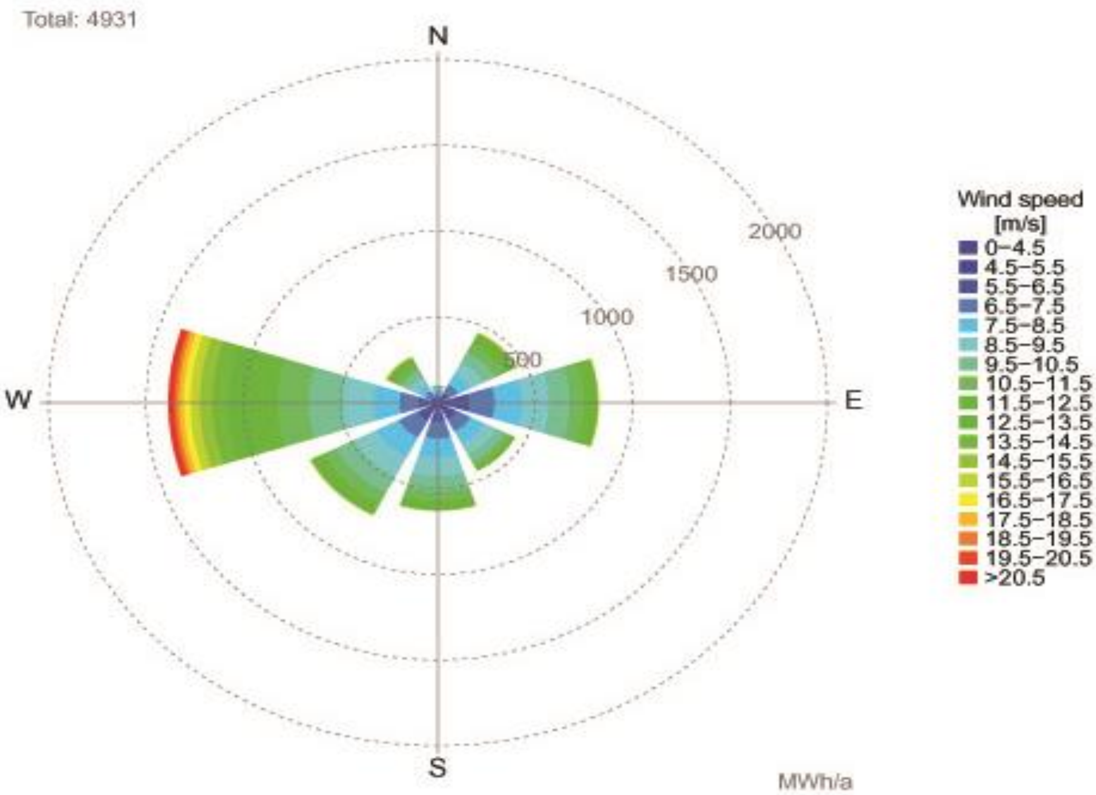


Figure 47: Engergy Production with Nordex Wind Turbine at 100m

Table 8: Summary of Energy production with Vestas and Nordex wind turbines at different heights

Wind Turbine Type	Annual Energy production at 80m [MWh/a]	Annual Energy production at 100m [MWh/a] NB: Vestas =105m
Vestas_V90_3.0MW	3827	4443
Nordex_N100_2.5MW	4384	4931

Source: Sulakshi & Rowland's Work, 2022

4.0 Conclusion

For vestas wind turbine, the total wind energy generated is 3827 [MWh/a] and 4443 [MWh/a] for 80m and 105m respectively. Meanwhile for nordex the total wind energy generated is 4384 [MWh/a] and 4931 [MWh/a] for 80m and 100m respectively. For Lebork, the Nordex_N100_2.5MW wind turbine seems to be more efficient and better suited for the site.

The various analysis carried out in this study has revealed that wind speed are stronger in winter months than the summer months, and as well as in day time than night time. Wind speed greatly influenced the amount of power and energy generated from the wind turbines. A very low wind speed generates a completely small or zero energy. While higher wind speeds generated much higher energy. Similarly, hub height also influences the power and the amount of energy generated. The higher the hub height, the more the energy likely to be generated, and the lower the hub height the lower the energy likely to be generated. Adequate consideration should be given to direction of wind in wind resource analysis as it greatly helps to reveal the sector with the most abundant and as well as the strongest winds which are all necessary in planning the installation and the micro-siting of a wind turbine or a wind farm.

Section B

KOSZALIN

Station Analysis

1.0 Wind Resource Assessment for Koszalin

A wind resource assessment involves analyzing the wind speed distribution, wind direction distribution, wind shear, annual energy production of proposed wind turbine installations. Case study 2 assesses the fundamental aspects of a wind resource assessment using meteorological data collected in the Koszalin meteorological station. Goal is to analyze the wind resource data from Koszalin meteorological station and determine the suitability of the Koszalin as a site for wind energy production.

Table 1: Information on Wind Resources Assessment Site, Koszalin

Location	Koszalin (indicated in figure 1)
Coordinates	54.20, 16.15
Name of Data file	121050
Elevation	15 m
Distance to Karwice	30.4 km
Wind Speed 10 m 100 m	 5.57 m/s 7.12 m/s
Power Density at 100 m	387.05 W/m^2

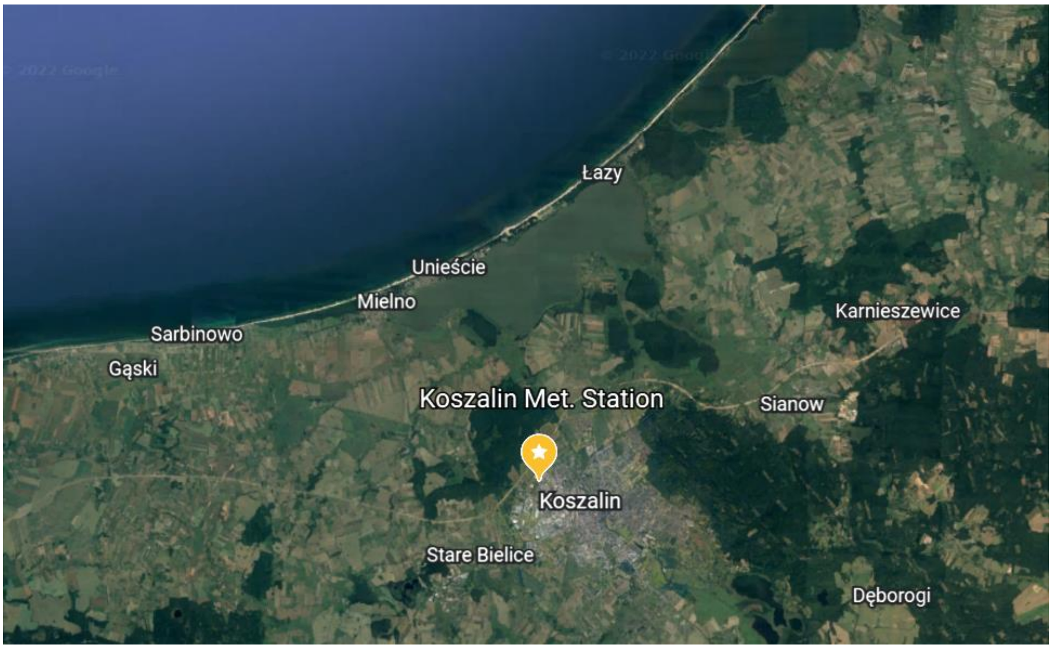


Figure 1: Satellite Imagery of the Study Area indicated in yellow mark.

Source: *(Google Earth, 2022)*

1.1 Koszalin Station – Climate Characteristics

2.1 Data Availability

The availability is the number of pairs of valid wind speed and valid wind direction data samples as a percentage of the total possible for the measurement period (Zdunek, 2022),

$$Availability = \frac{N(v_{valid} \wedge v_{valid})}{N}$$

Where;

N: Total possible number of samples

$v_{valid} \wedge v_{valid}$: pair of valid wind speed and direction data

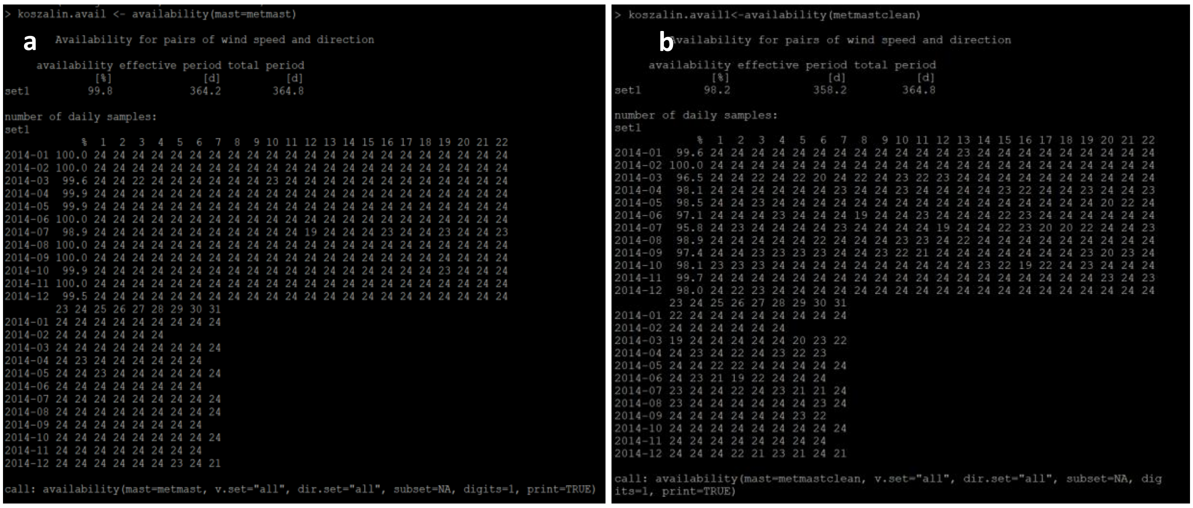


Figure 2: Data Availability of Wind Speed & Wind Direction at 10 m Height before and after cleaning Source: (Sulakshi & Rowland's Work)

Total availability of original data before performing cleaning function is 99.8 %, effective period is 364.2 days and total period is 364.8 days of a set of wind speed and direction. After removing data below 0.4 and NA data points, the total data availability for Koszalin meteorological station is 98.2 %, out of 364.8 of total days, 358.2 days were selected as effective days.

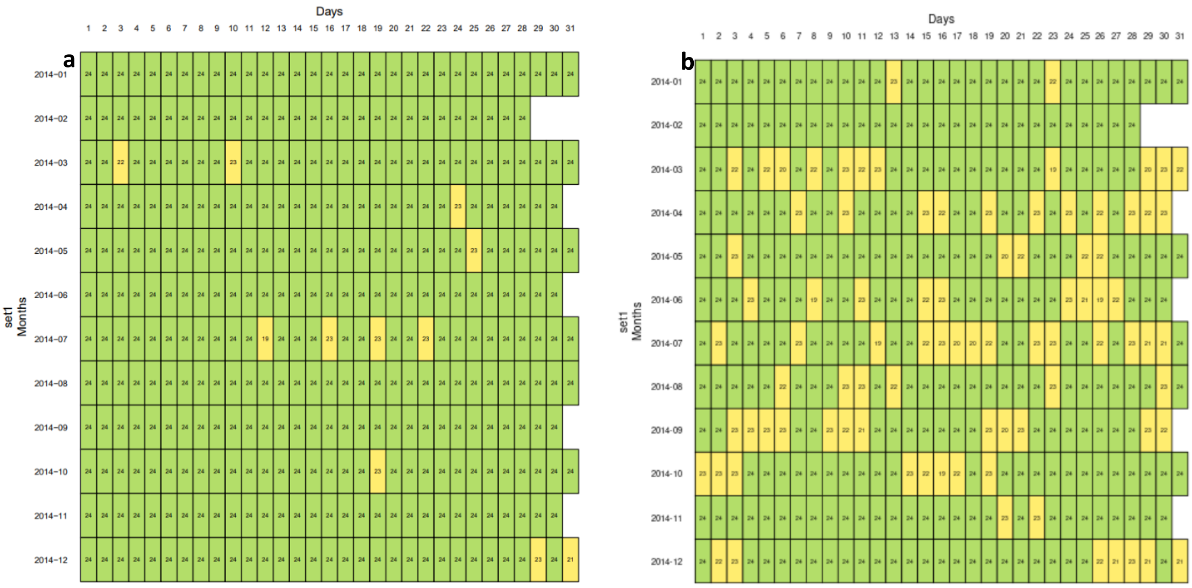
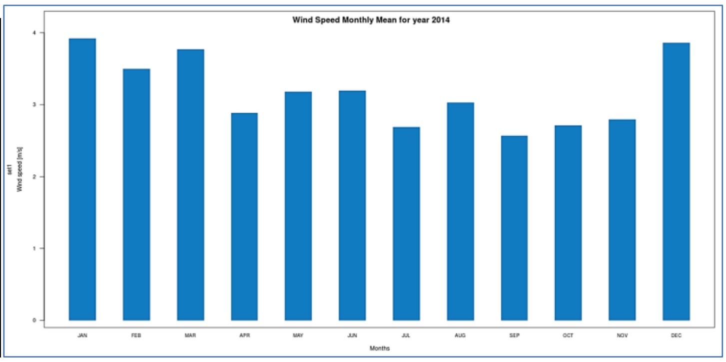


Figure 3: Data Availability Calendar Plot before (a) and after (b) Cleaning the Dataset. Source: (Sulakshi & Rowland's Work)

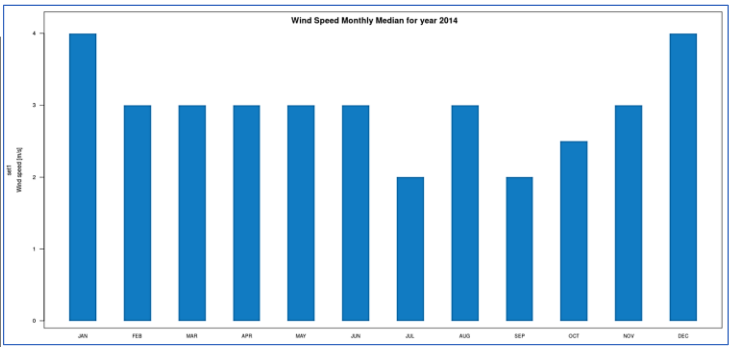
Calendar plots depicted by figure 5a, and b, indicated the data availability throughout year 2014 for Koszalin. Both wind speed and wind direction data availability illustrated by green color while data unavailability or partial data availability represented by yellow color. In original dataset, there were 11 days with data unavailability.

2.2 Statistical Analysis

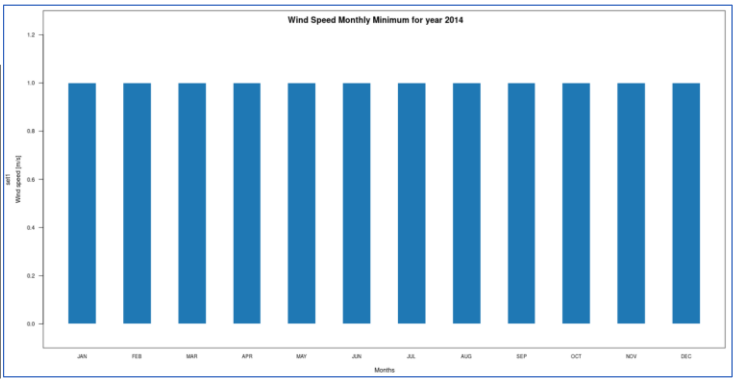
```
> koszalin.stats <- month.stats(mast=metmastclean)

          Monthly statistics

set1
                  2014  mean mean of months
JAN              3.923 3.923          3.923
FEB              3.496 3.496          3.496
MAR              3.767 3.767          3.767
APR              2.890  2.89           2.89
MAY              3.180  3.18           3.18
JUN              3.197 3.197          3.197
JUL              2.693 2.693          2.693
AUG              3.031 3.031          3.031
SEP              2.571 2.571          2.571
OCT              2.714 2.714          2.714
NOV              2.792 2.792          2.792
DEC              3.863 3.863          3.863
mean             3.178 3.178
mean of months 3.176                  3.176
```



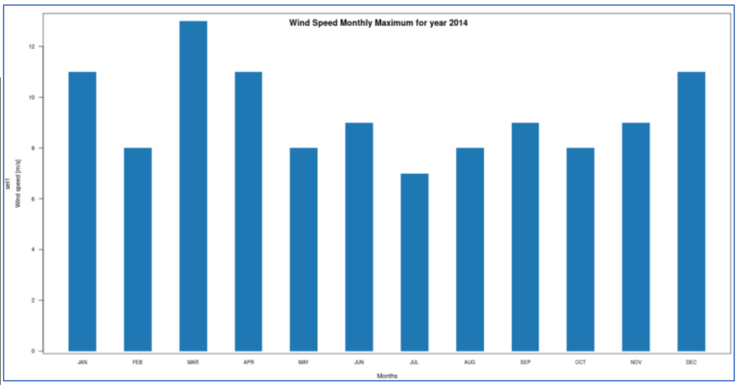

```
> koszmed=month.stats(mast=metmastclean, fun="median")

         Monthly statistics

set1
                 2014 median median of months
JAN               4.0      4                4
FEB               3.0      3                3
MAR               3.0      3                3
APR               3.0      3                3
MAY               3.0      3                3
JUN               3.0      3                3
JUL               2.0      2                2
AUG               3.0      3                3
SEP               2.0      2                2
OCT               2.5    2.5              2.5
NOV               3.0      3                3
DEC               4.0      4                4
median            3.0      3
median of months  3.0                       3
```




```
> koszmin=month.stats(mast=metmastclean, fun="min")

          Monthly statistics

set1
     2014 min
JAN     1   1
FEB     1   1
MAR     1   1
APR     1   1
MAY     1   1
JUN     1   1
JUL     1   1
AUG     1   1
SEP     1   1
OCT     1   1
NOV     1   1
DEC     1   1
min     1   1
```




```
> koszmax=month.stats(mast=metmastclean, fun="max")

          Monthly statistics

set1
     2014 max
JAN    11  11
FEB     8   8
MAR    13  13
APR    11  11
MAY     8   8
JUN     9   9
JUL     7   7
AUG     8   8
SEP     9   9
OCT     8   8
NOV     9   9
DEC    11  11
max    13  13
```



```
> koszsd=month.stats(mast=metmastclean, fun="sd")

        Monthly statistics

set1
     2014    sd
JAN 1.873 1.873
FEB 1.220 1.220
MAR 2.341 2.341
APR 1.572 1.572
MAY 1.535 1.535
JUN 1.742 1.742
JUL 1.346 1.346
AUG 1.516 1.516
SEP 1.358 1.358
OCT 1.344 1.344
NOV 1.276 1.276
DEC 1.912 1.912
sd  1.684 1.684
```

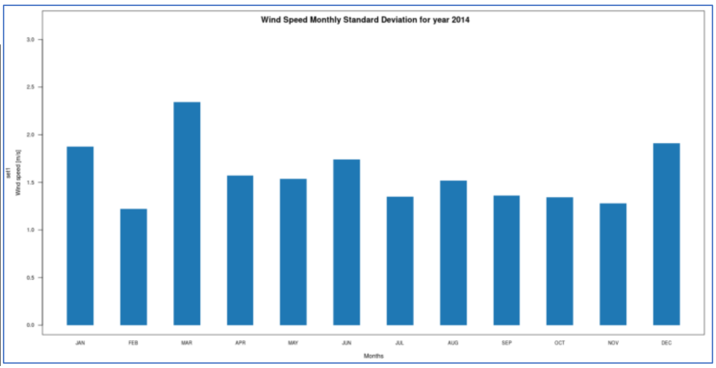


Figure 4: Statistical Analysis Data and Plots of a.) Mean, b.) Median, c.) Max, d.) Minimum, And e.) Standard Deviation of Koszalin. Source: (Sulakshi & Rowland's Work)

Monthly mean wind speed variation for Koszalin station in year 2014 is depicted by figure 4a. Winter months, December to March exhibits higher mean wind speed values, whereas January possesses the highest wind speed of 3.923 m/s. Autumn season shows the lowest mean wind speed values with the lowest value of 2.571 m/s in September. Minimum mean wind speed value for every month for year 2014 depicted as 1 m/s as shown in figure 4c. The highest value of maximum mean wind speed of 13 m/s recorded in March while July shows the least value of maximum mean speed 7 m/s.

2.2 Wind Speed Distribution

Estimation of the power output of a wind turbine requires the wind speed distribution, since the frequency distribution delineate the number of occurrences in the data record period categorized within particular ranges or bins. In this report, 1 m/s wide speed bins were used for the histograms, covering wind speeds and frequencies which is known as Weibull distribution plots. The Weibull distribution is a mathematical function that is often used to represent the wind speed frequency distribution at a site (Brower, 2012).

The wind speed distribution at a location can generally be delineated by the Weibull probability density function given by following equation

$$f(v) = \frac{k}{A} \times \frac{v^{k-1}}{A} \times e^{-(v/A)^k}$$

where

f(v): Frequency occurrence of occurrence of wind speed v

A: Scale parameter

k: Shape parameter

The scale parameter (A) is a measure for the characteristic wind speed of the distribution. The shape parameter (k), defines the shape of a Weibull distribution and possesses a value of between 1 and 3. A small value for k denotes vastly fluctuating winds, while consistent winds are distinguished by a larger k. Also, the higher the value of k, the higher the median wind speed.

The figure 1 illustrated below, presents the measured wind speed data of Koszalin as a distribution in blue bins and a fitted Weibull distribution in red line

```
> wei8<-weibull(mast=metmastclean, v.set=1, num.sectors=8)
146 NA found and excluded from calculation

        Weibull parameters

        A      k wind speed frequency
    [m/s]    [-]      [m/s]       [%]
N   2.963  2.04       2.625    12.168
NE  2.729 2.064       2.417     5.328
E   2.494 2.355        2.21     6.968
SE  3.554 2.551       3.155    21.824
S   3.256 2.297       2.884    24.395
SW  3.869  2.32       3.428     11.61
W   5.484 2.167       4.857    11.773
NW  4.076 1.952       3.614     5.933
all 3.582 1.907       3.178       100
```

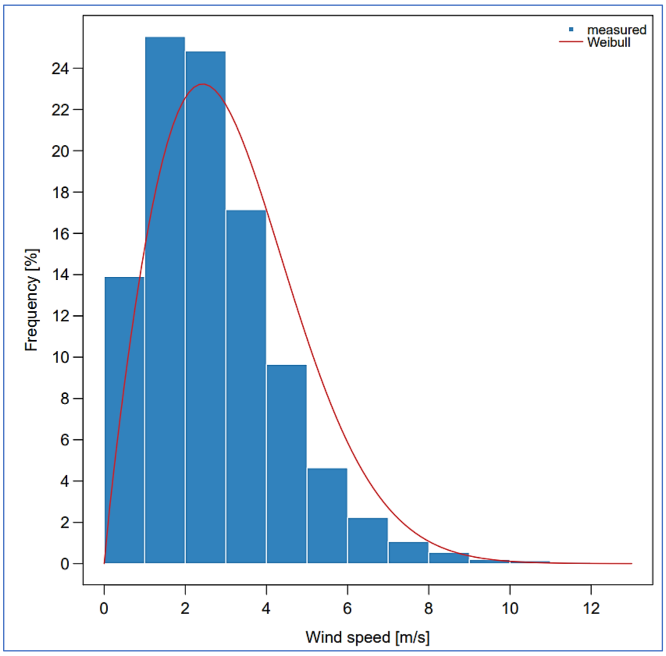


Figure 5: Measured Wind Speed Frequency Distributions and Fitted Weibull Curve. Source: (Sulakshi & Rowland's Analysis)

In the Weibull distribution, highest k value of 2.551 can be seen from South-Easterly wind of scale parameter (A) of 3.55 m/s which means winds from that direction possesses less fluctuating and higher constant characteristics. However, the overall k value calculated as 1.907 which is a relatively lower value denoting fluctuating wind flows in the site.

```
> koszalinwb

          Weibull parameters

            A      k wind speed frequency
        [m/s]    [-]      [m/s]       [%]
N   2.981 2.068        2.64     7.829
NNE 2.698 1.939       2.393     5.212
ENE 2.543 2.143       2.252     2.908
E    2.36 2.397       2.092     3.804
ESE 3.303 2.621       2.934    10.807
SSE  3.53  2.39       3.129    20.789
S   3.221 2.324       2.854    13.495
SSW 3.472 2.415       3.078     9.714
WSW 4.261 2.178       3.774     7.503
W   5.629 2.124       4.985     7.818
WNW 5.039 2.309       4.464     5.363
NNW 3.268 1.962       2.897     4.758
all 3.582 1.907       3.178       100
```

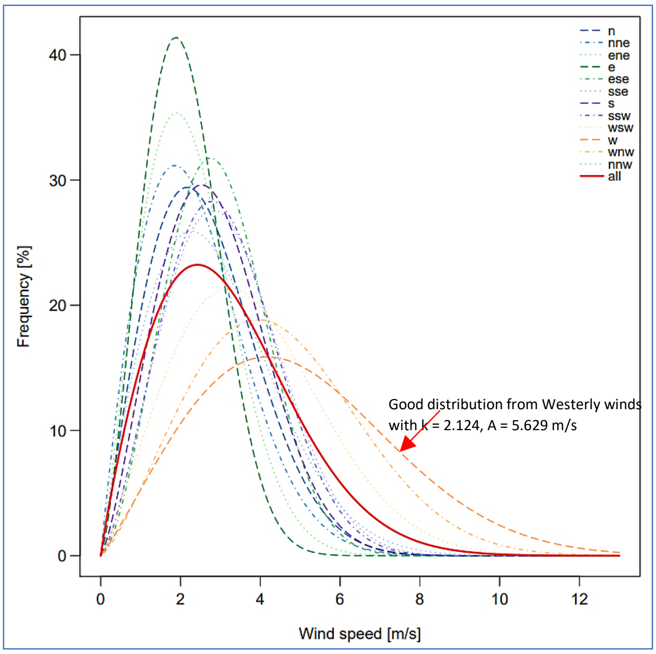


Figure 6: Weibull distributions with scale parameter (A) and varying shape parameters (k) for 12 directions. Source: (Sulakshi & Rowland's Work)

Wind flown from west, and west-north-west represents good Weibull distribution fit as shown in figure 3 denoting consistent winds with frequency occurrences of 7.818% and 5.363%.

2.3 Wind Speed Variability

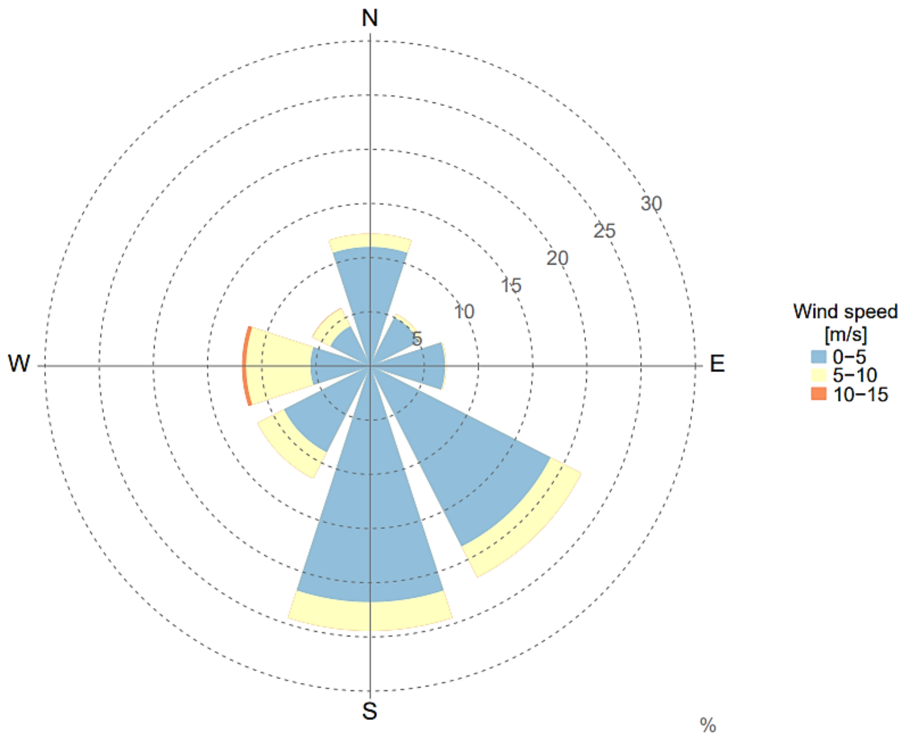
The directional distribution of the wind resource is a key factor influencing the design of a wind project because the wind speed distribution frequently changes with wind direction, type of the season, height above ground, and time of day. This relationship between wind speed and wind direction illustrates as a wind rose plot, which includes wind speed vs. wind direction in polar coordinates as depicted by figure 4. In this report, wind rose plots generated for 8 directions with 5m/s bins, and 12 directions with 1m/s bins.

As shown in 8 sector wind rose plot in figure 4 a, Southerly wind flown at a 180^{0} angle occurred the most with total frequency of 24.395% with 21.731% occurrence for 0 – 5 m/s wind speed, 2.664% occurrence for 5 – 10 m/s wind speed, and no occurrence for 10 – 15 m/s. Even though, southerly wind is the mostly occurred wind, it is not strong enough. Nevertheless, westerly wind flown at a 270^{0} angle includes strong velocities of 10 – 15 m/s with 0.384% frequency which is a small occurrence. However, for overall site, 0 – 5 m/s wind occurred 81.433%, 5 – 10 m/s wind occurred 18.148%, and 10 – 15 m/s occurred 0.419%.

a

```
> freq8=frequency(mast=metmastclean, v.set=1, num.sectors=8)

        Frequency

    wind speed  total    0-5    5-10 10-15
         [m/s]    [%]    [%]     [%]   [%]
N        2.625 12.168 10.935  1.233
NE       2.417  5.328  4.944  0.384
E         2.21  6.968  6.852  0.116
SE       3.155 21.824 18.613  3.211
S        2.884 24.395 21.731  2.664
SW       3.428  11.61  8.853  2.757
W        4.857 11.773  5.456  5.933 0.384
NW       3.614  5.933  4.048   1.85 0.035
all      3.178    100 81.433 18.148 0.419
```

8 Sector Wind Rose Plot of Koszalin from 01/01/2014 to 31/12/2014



b

```
> frequency(mast=metmastclean, v.set=1, bins=1:25)

        Frequency

    wind speed  total 0-1    1-2    2-3    3-4    4-5   5-6   6-7   7-8   8-9
         [m/s]    [%] [%]    [%]    [%]    [%]    [%]   [%]   [%]   [%]   [%]
N         2.64  7.829        1.815   2.21  1.815  1.175 0.617 0.174 0.023
NNE      2.393  5.212        1.524  1.664  0.989  0.582 0.396 0.058
ENE      2.252  2.908        0.768  1.117  0.686  0.233  0.07 0.035
E        2.092  3.804         1.07  1.629  0.838  0.221 0.047
ESE      2.934 10.807        1.268  2.757   3.49   2.28 0.768 0.209 0.035
SSE      3.129 20.789        1.617  5.898  6.329  3.758 2.024 0.803 0.233 0.093
S        2.854 13.495         1.78  4.293  3.525  2.455 1.024 0.302 0.105 0.012
SSW      3.078  9.714        1.221  2.431  2.443  2.106 1.082 0.361  0.07
WSW      3.774  7.503         0.64  1.396  1.698  1.373 1.012 0.826 0.291 0.174
W        4.985  7.818        0.663  0.779  0.849  1.128 1.245 1.082 0.896 0.535
WNW      4.464  5.363        0.465  0.465  0.907  0.942 1.024 0.651   0.5 0.209
NNW      2.897  4.758        1.082  0.896  1.268  0.896 0.349  0.14 0.081 0.047
all      3.178    100       13.913 25.535 24.837 17.148 9.656 4.642 2.234  1.07
     9-10 10-11 11-12 12-13   >13
      [%]   [%]   [%]   [%]   [%]
N
NNE
ENE
E
ESE
SSE 0.035
S
SSW
WSW 0.081 0.012
W   0.291  0.14 0.128 0.058 0.023
WNW  0.14 0.047 0.012
NNW
all 0.547 0.198  0.14 0.058 0.023
```

16 Sector Wind Rose Plot of Koszalin from 01/01/2014 to 31/12/2014

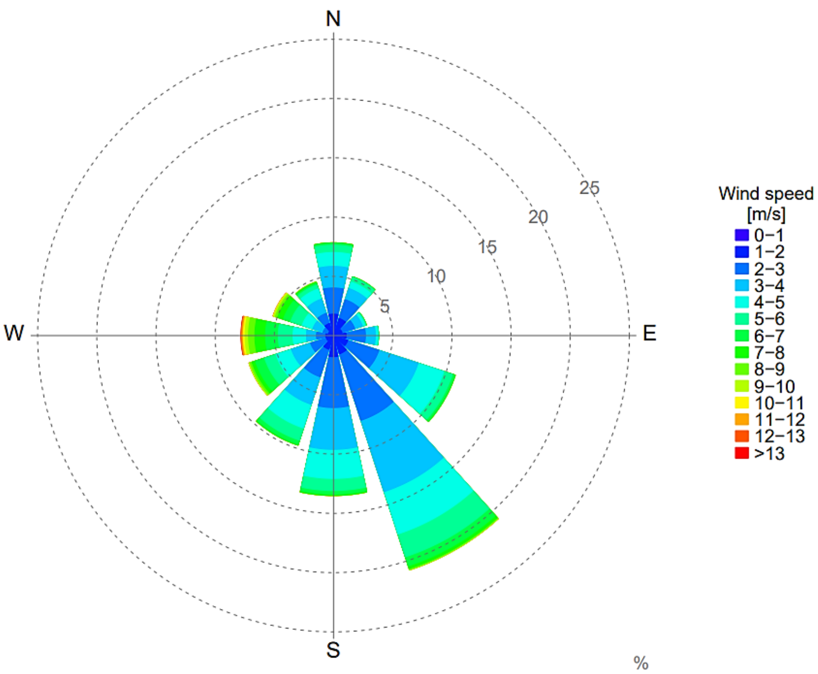


Figure 7: Wind Rose Plot at 10m for Koszalin for 2014. a.) 8 Sector Wind Rose, b.) 12 Sector Wind Rose Source: (Sulakshi & Rowland's Work)

From durational plot depicted in figure 5, wind tends to be stronger during the day showing highest wind velocity at 12:00 pm because sun heats up the Earth surface, which discomposes the current stratification of the temperature. Consequently, there is increased motion in the air due to convection. Nighttime shows weaker winds as the air temperature at night is relatively stable, with colder, denser air near the surface and warmer air higher up.

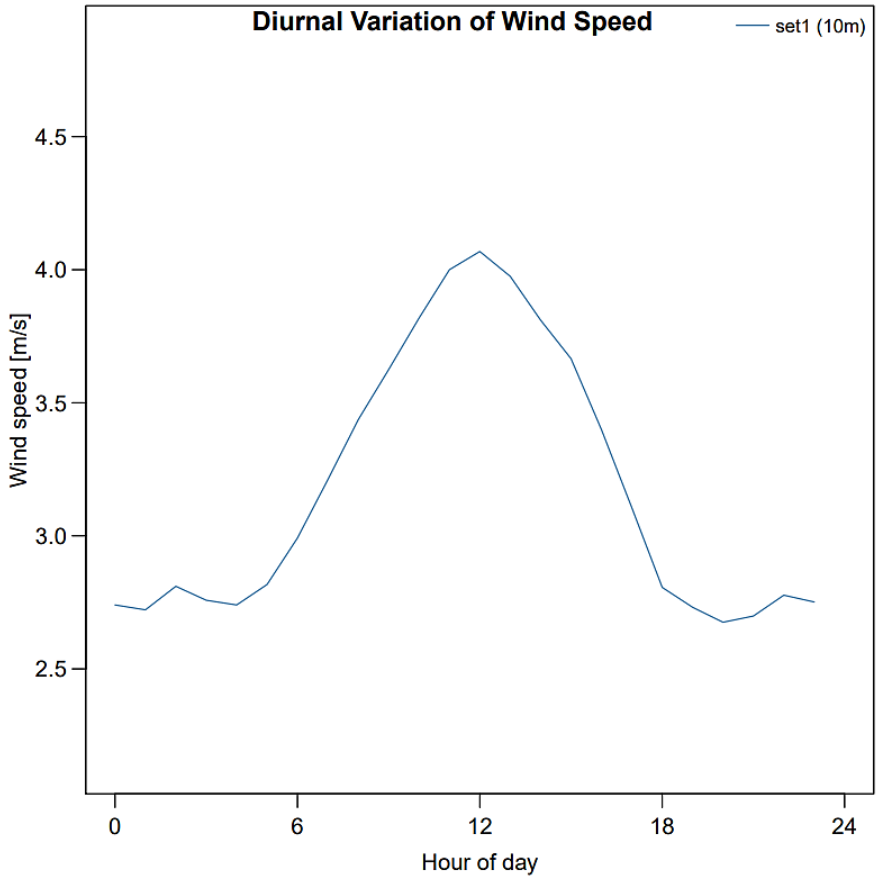


Figure 8: Diurnal Patterns of Wind Velocity, Koszalin at 10m. Source: Sulakshi & Rowland's Work

Conversely, wind tends to be stronger during the winter than the summer in Koszalin as shown by yearly time series plots in figure 6 a. Annual mean temperature for 2014 shown as 3.172 m/s showing higher fluctuations from mean wind speed. Highest wind speed occurred in March with more than 12 m/s. Yearly time series exhibits a seasonality pattern. Wind data for November has selected to plot the monthly time series. During the beginning to mid-November, wind speed shows pretty much consistently varying pattern. However, a sudden shift of wind speed more than 8 m/s is visible at the last week of November. Lowest speed exhibits during the end of the November.

Weekly time series is plotted from 07/11/2014 to 14/11/2014 to detect specific patterns. 10th and 12th of November represents the highest wind speeds for that week. Daily change of wind with time for 14th of November shows that highest velocities occurred during night-time.

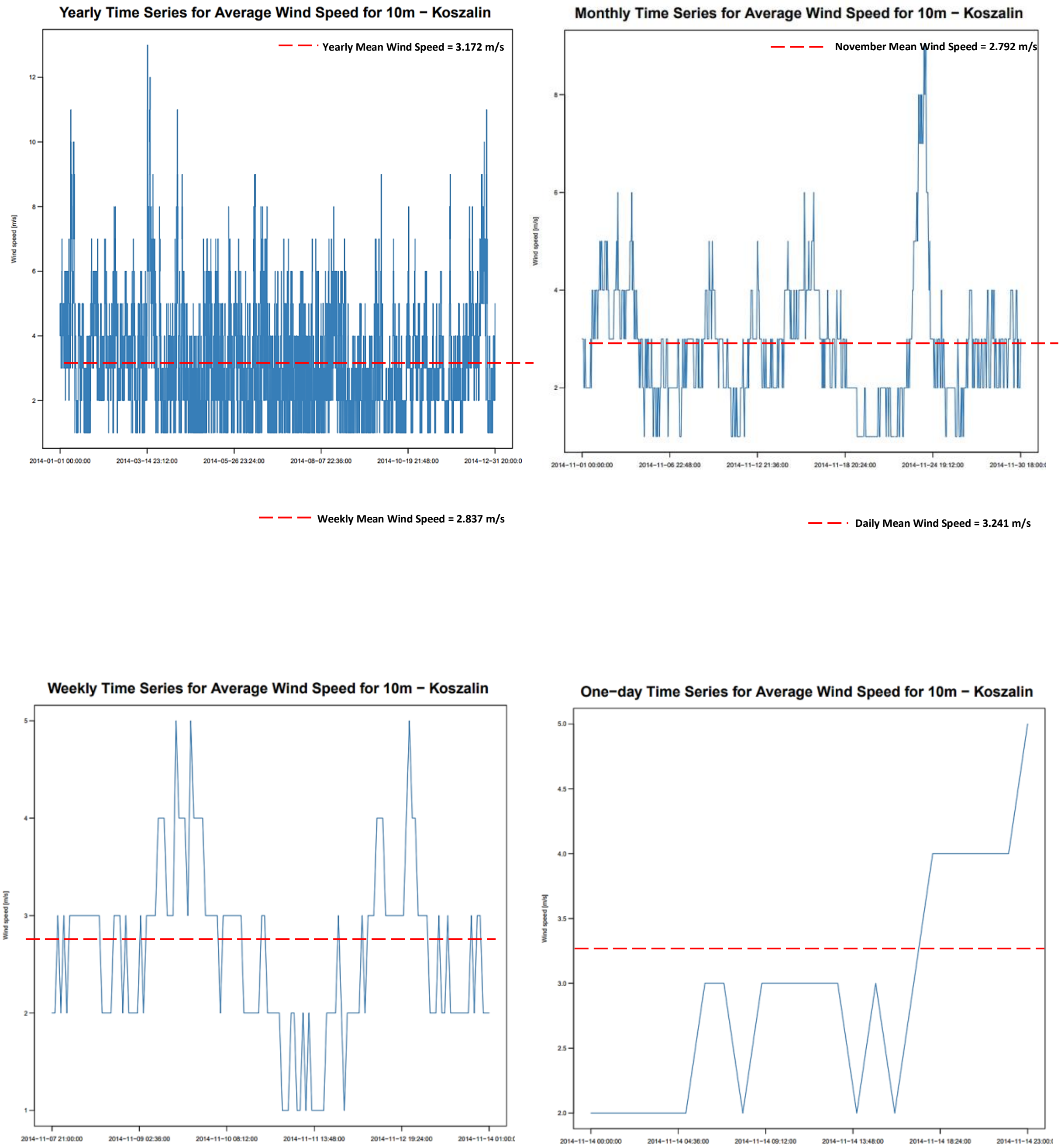
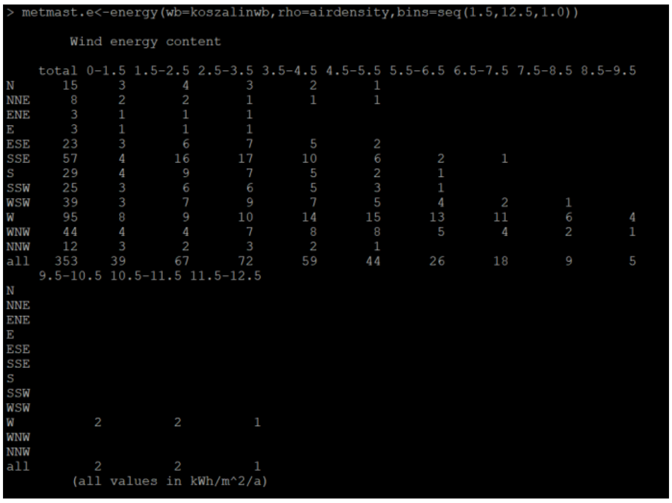


Figure 9:Wind speed Distribution at 10 m Sea Level Height at Koszalin Meteorological Station a.) Yearly, b.) Monthly, c.) Weekly, d) Daily. Source: (Sulakshi & Rowland's Work).

2.4 Energy Distribution and Variability

In 2.3 wind speed variability section, westerly winds recognized as the strongest wind occurred in Koszalin site as depicted by the wind rose plots in figure 6 a, and b. In this section, wind energy content per direction has been analyzed. Highest wind energy of 95 kWh/m^2/a generated due to Westerly winds from 270 ^{0} with strong winds more than 11.5 m/s velocities. This is due to higher wind velocities causes increase in the kinetic energy of the wind particles causing higher energy generations. Easterly winds generated the lowest energy of 3 kWh/m^2/a. The total wind energy content generated in Koszalin site is analyzed as 353 kWh/m^2/a.



```
> metmast.e<-energy(wb=koszalinwb,rho=airdensity,bins=seq(1.5,12.5,1.0))

        Wind energy content

    total 0-1.5 1.5-2.5 2.5-3.5 3.5-4.5 4.5-5.5 5.5-6.5 6.5-7.5 7.5-8.5 8.5-9.5
N      15     3       4       3       2       1
NNE     8     2       2       1       1       1
ENE     3     1       1       1
E       3     1       1       1
ESE    23     3       6       7       5       2
SSE    57     4      16      17      10       6       2       1
S      29     4       9       7       5       2       1
SSW    25     3       6       6       5       3       1
WSW    39     3       7       9       7       5       4       2       1
W      95     8       9      10      14      15      13      11       6       4
WNW    44     4       4       7       8       8       5       4       2       1
NNW    12     3       2       3       2       1
all   353    39      67      72      59      44      26      18       9       5
    9.5-10.5 10.5-11.5 11.5-12.5
N
NNE
ENE
E
ESE
SSE
S
SSW
WSW
W          2         2         1
WNW
NNW
all        2         2         1
        (all values in kWh/m^2/a)
```

Total wind energy content per direction sector in Koszalin

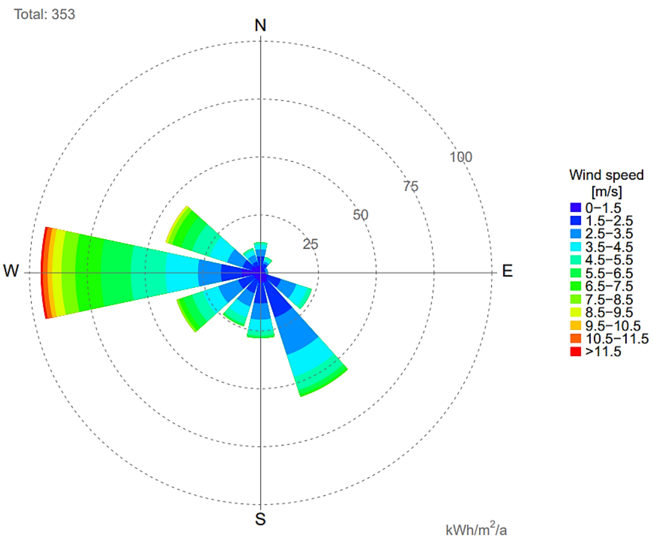


Figure 10: Energy Rose Plots at 10 m Height for Koszalin. Source: (Sulakshi & Rowland's Work)

2.5 Wind Shear Profile

The wind shear which is known as the rate of change in horizontal wind speed with height is expressed as a dimensionless power-law exponent known as alpha, α. For different topographies, there are different alpha values. Koszalin site identified as flat terrain open land cover, therefore, the alpha value is selected as 0.22 (Zdunek, 2022).

Figure 11: Koszalin Site Exhibits a Flat Terrain with Open Land Cover. Source: *(Google Earth, 2022)*

Wind speed measurements at wind turbine's hub height is unavailable in the dataset for Koszalin site, therefore, using available site data at 10 m height is applied to perform curve fit. Thereby, wind speeds at higher heights can be extrapolated using the 'windprofile' function in bRreeze program. For energy calculations, only the wind speeds at hub height are used. However, it is very essential to consider the range of wind speeds passing through the turbine rotor's swept area. It has been shown that the wind shear profile alters the performance of wind turbines (Lam, 2013). Even though, Koszalin site is an open land cover flat terrain, the location has considerably strong shear as depicted in figure 11.

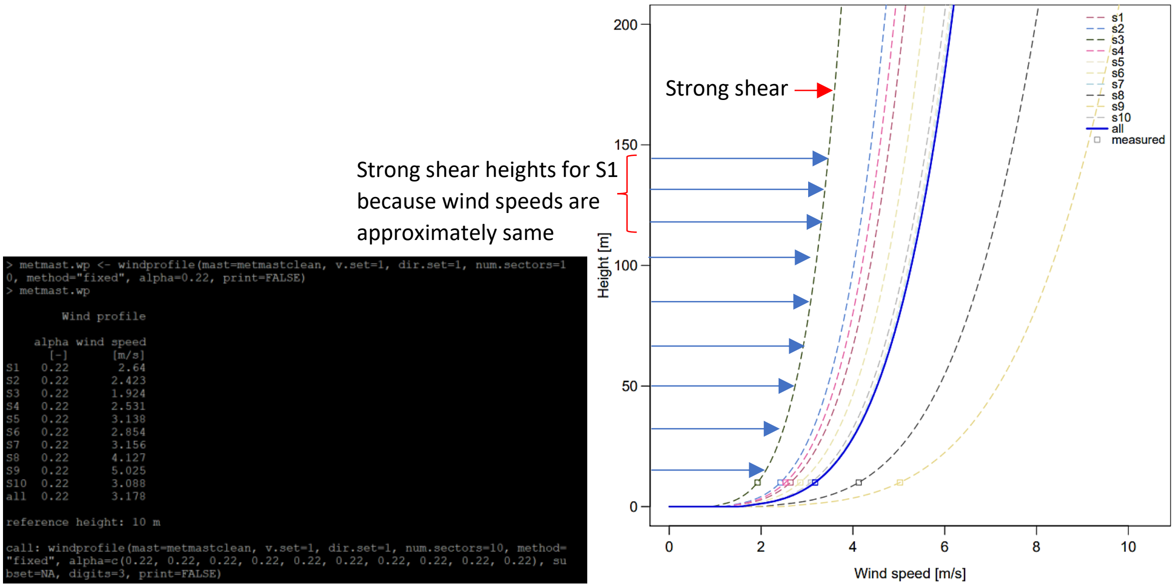


Figure 12: Profiles of Wind Speed with 10 m Height for the Exponent Value, α (0.22). Source: (Sulakshi & Rowland's Source)

2.6 Wind Turbine Power Curve

The power curve of a wind turbine is its power output as a function of the wind speed. Wind shear is directly affecting the power generation because air moving at a constant velocity through a wind turbine's swept area is very essential for higher power generations.

The power output largely depends on the wind speed as shown in the power equation below (Lam, 2013).

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

Where;

P: Power

ρ: Air density

A: Wind turbine's swift area

v: Wind speed

Air density is calculated using the ideal gas law,

$$\rho = \frac{P}{RT}(\frac{kg}{m^3})$$

Where;

P: Air pressure at the meteorological station (Pa)

R: Specific gas constant of dry air (287.04 J/kg K)

T: Air temperature at the meteorological station (K)

```
> P<-mean(table$V7)*100
> T<-mean(table$V4)+273.15
> R<-287
> airdensity<-P/T/R
> airdensity
[1] 1.244204
```

Figure 13: Air Density Calculation for Koszalin Site.

Air density for Koszalin meteorological station calculated as 1.24 kg/m^3.

In this case study two types of turbines were considered; Vestas_v90_3MW turbine, and Nordex_N100_2.5MW turbine.

Table 2: Power Characteristics of Turbines

Turbine	Cut In		Rated		Cut Off	
	Power (kW)	Wind (m/s)	Power	Wind	Power	Wind
Vestas_v90_3MW	0	1	3000	17	3000	25
Nordex_N100_2.5MW	0	1	2500	13	2500	20

```
> vestas.v90 <- pc("Vestas_V90_3.0MW.pow")
> vestas.v90

        Power curve

description: Vesta V90 3mW 106.7dB(A)  (Manufacturer's table)
rated power: 3000
air pressure: 1.225

   wind speed power
         [m/s]   [kW]
1            1      0
2            2      0
3            3      0
4            4     77
5            5    190
6            6    353
7            7    581
8            8    885
9            9   1258
10          10   1641
11          11   2004
12          12   2353
13          13   2671
14          14   2888
15          15   2976
16          16   2997
17          17   3000
18          18   3000
19          19   3000
20          20   3000
21          21   3000
22          22   3000
23          23   3000
24          24   3000
25          25   3000
```

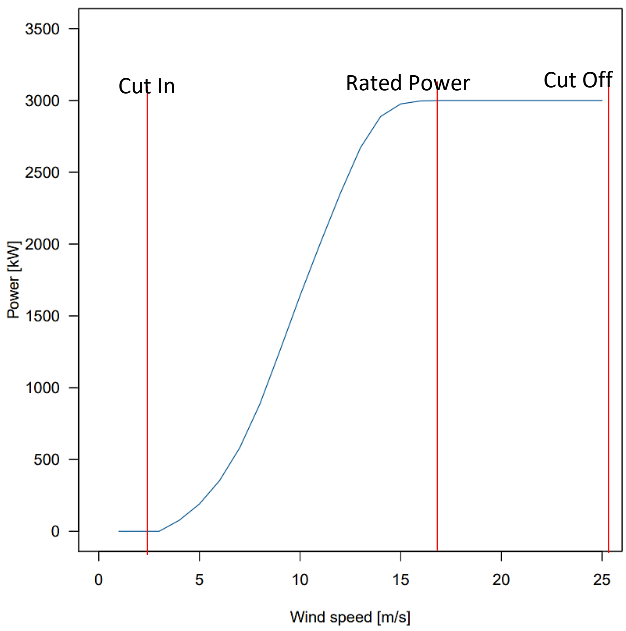


Figure 14: Vestas_v90_3MW Wind Turbine Power Curve. Source: (Sulakshi & Rowland’s Work)

The Vestas_v90_3MW turbine will not operate below the cut in wind speed value of 1 m/s due to insufficient torque preventing the turbine blades rotation. When the turbine starts, the power curve shows exponential rise from 0 to 3000 kW within the wind speed range approximately from 5 to 15 m/s. Eventually, the power ramps up for 3000 kW energy when the wind speed is around 15 m/s. Rated power stays within the wind speed of 15 to 25 m/s, when there are higher winds than cut off wind speed, the turbines are shutting down to prevent structural damages from heavy wind loads.

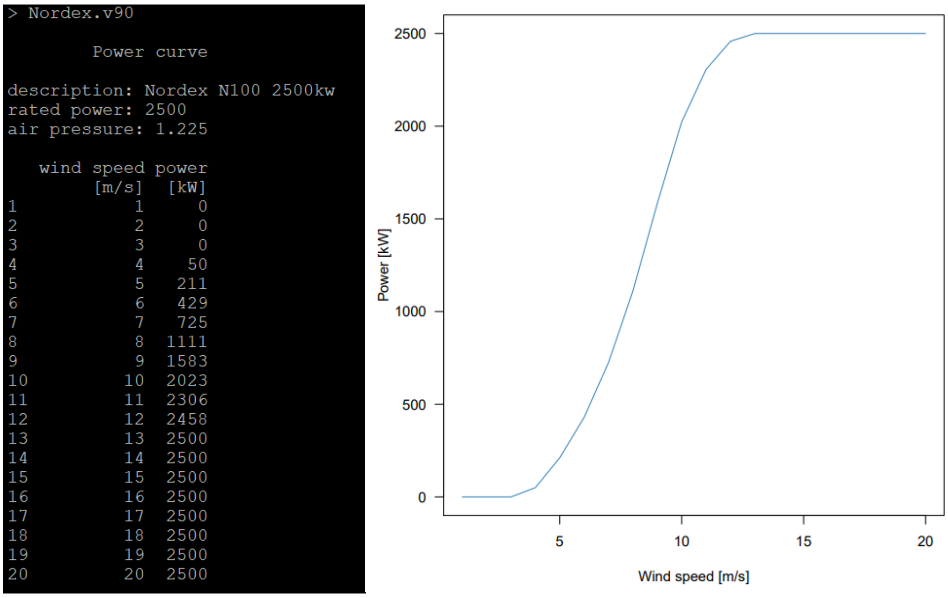


Figure 15: Nordex_N100_2.5MW Wind Turbine Power Curve. Source: (Sulakshi & Rowland's Work)

For Nordex_N100_2.5MW turbine, the power ramped up around 10 m/s wind speed for 2500 kW power.

2.7 Annual Energy Production (AEP)

One of the main goals of a wind resource assessment is to calculate the annual energy production from selected turbines at Koszalin site. This AEP determines financial feasibility of the project. The wind turbine power curve and wind speed data were used to calculate AEP. In this study, different hub heights for selected turbines were considered.

Table 3: Annual Energy Production from Vestas_v90_3MW & Nordex_100N_2.5MW Turbines

Vestas_v90_3MW	Nordex_100N_3.5MW
Annual Energy Production (MWh/a) 80 m hub height = 3239 105 m hub height = 3795	Annual Energy Production (MWh/a) 80 m hub height = 3720 100 m hub height = 4227

```
> aepvest80<-aep(profile=metmast.wp, pc=vestas.v90, hub.h=80, rho=airdensity,bin
s=seq(4.5,20.5,1.0))

        Annual energy production

      wind speed operation   total   0-4.5 4.5-5.5 5.5-6.5 6.5-7.5 7.5-8.5
           [m/s]     [h/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a]
N          4.172       686     144       4      20      27      28      24
NNE        3.781       457      74       3      12      15      14      11
ENE        3.558       255      30       2       7       7       6       3
E          3.305       333      26       3       8       7       3       1
ESE        4.636       947     229       6      35      51      52      40
SSE        4.945      1821     578       9      60      94     113     109
S           4.51      1182     286       7      39      56      60      51
SSW        4.863       851     255       4      29      44      52      48
WSW        5.963       657     375       2      17      31      44      55
W          7.877       685     726       2      12      24      40      59
WNW        7.054       470     394       1      10      20      32      45
NNW        4.578       417     122       2      12      17      20      20
total      5.022      8760    3239      45     261     393     464     466
      8.5-9.5 9.5-10.5 10.5-11.5 11.5-12.5 12.5-13.5 13.5-14.5 14.5-15.5
      [MWh/a]  [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]
N          17       10         5         2         1
NNE         8        4         2         1
ENE         2        1
E
ESE        23        9         3         1
SSE        84       52        26        11         4         1
S          34       18         8         3         1
SSW        35       21        10         4         1
WSW        58       53        42        30        19        11         5
W          76       86        88        83        72        58        43
WNW        54       56        51        42        32        21        13
NNW        18       13         8         5         2         1
total     409      323       243       182       132        92        61
      15.5-16.5 16.5-17.5 17.5-18.5 18.5-19.5 19.5-20.5   >20.5
        [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a] [MWh/a]
```

```
N
NNE
ENE
E
ESE
SSE
S
SSW
WSW             2         1
W              30        20        13         8         5       5
WNW             7         4         2         1
NNW
total          39        25        15         9         5       5

capacity factor: 0.123

call: aep(profile=metmast.wp, pc=vestas.v90, hub.h=80, rho=1.244204, avail=1, bi
ns=c(0, 4.5, 5.5, 6.5, 7.5, 8.5, 9.5, 10.5, 11.5, 12.5, 13.5, 14.5, 15.5, 16.5,
17.5, 18.5, 19.5, 20.5), sectoral=FALSE, digits=c(3, 0, 0, 3), print=TRUE)
```

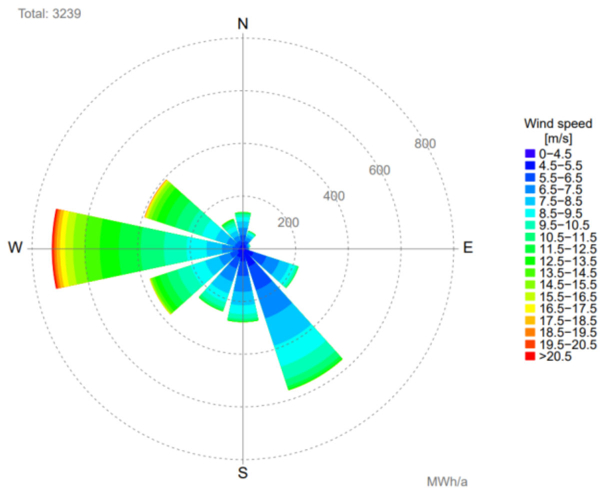


Figure 16: Annual Energy Production for Vestas_v90_3MW Turbine at 80 m Hub Height. Source: (Sulakshi & Rowland's Work)

For Vestas_v90_3MW turbine at 80 m hub height, the highest annual energy of 726 MWh/a generated due to westerly wind flow at a 270^{0} and the highest percentage of this energy produced from 10.5 – 11.5 m/s speed winds. Second highest annual energy of 578 MWh/a generated due to south-south-east wind blown at 150 ^{0} angle. Lowest annual energy of 26 MWh/a generated from easterly wind. Total annual energy production for 80 m from Vestas_v90_3MW turbine is 3239 MWh/a.

```
> aepvest105<-aep(profile=metmast.wp, pc=vestas.v90, hub.h=105, rho=airdensity,bins=seq(4.5,20.5,1.0))

        Annual energy production

      wind speed operation   total   0-4.5 4.5-5.5 5.5-6.5 6.5-7.5 7.5-8.5
           [m/s]     [h/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a] [MWh/a]
N          4.429       686     174       4      20      29      32      30
NNE        4.014       457      90       3      12      16      17      15
ENE        3.778       255      37       2       7       8       7       5
E          3.509       333      32       3       9       9       5       2
ESE        4.922       947     278       5      34      53      61      53
SSE        5.249      1821     694       8      58      96     123     129
S          4.788      1182     347       6      38      58      68      64
SSW        5.163       851     306       4      27      45      57      58
WSW         6.33       657     436       2      16      30      44      57
W          8.363       685     807       1      11      23      38      57
WNW        7.489       470     448       1       9      19      31      45
NNW         4.86       417     146       2      11      18      22      24
total      5.332      8760    3795      41     252     404     505     539
      8.5-9.5 9.5-10.5 10.5-11.5 11.5-12.5 12.5-13.5 13.5-14.5 14.5-15.5
      [MWh/a]  [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]
N          23       15         8         4         2         1
NNE        11        7         3         2         1
ENE         3        1
E           1
ESE        36       18         7         2
SSE       111       77        44        21         9         3         1
S          48       29        14         6         2         1
SSW        48       32        17         8         3         1
WSW        64       62        52        40        28        17        10
W          76       89        93        91        83        70        54
WNW        56       61        59        51        41        30        19
NNW        22       17        12         7         4         2         1
total     499      408       309       232       173       125        85
      15.5-16.5 16.5-17.5 17.5-18.5 18.5-19.5 19.5-20.5   >20.5
        [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a]   [MWh/a] [MWh/a]
```

```
N
NNE
ENE
E
ESE
SSE
S
SSW
WSW             5         2         1
W              40        28        19        12         8      10
WNW            11         6         3         2         1       1
NNW
total          56        36        23        14         9      11

capacity factor: 0.144

call: aep(profile=metmast.wp, pc=vestas.v90, hub.h=105, rho=1.244204, avail=1, bins=c(0,
.5, 17.5, 18.5, 19.5, 20.5), sectoral=FALSE, digits=c(3, 0, 0, 3), print=TRUE)
```

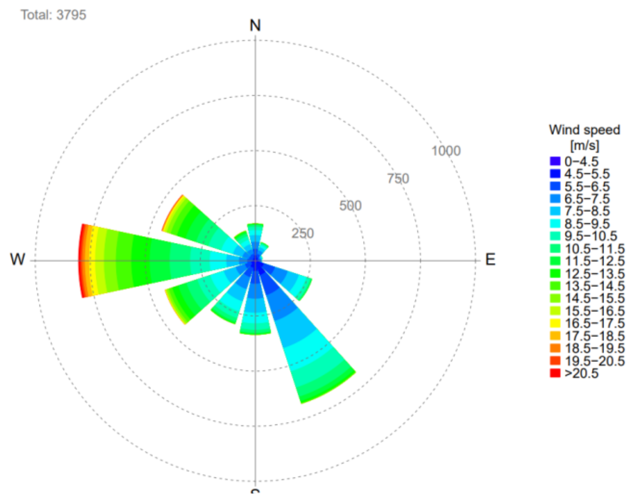


Figure 17: Annual Energy Production for Vestas_v90_3MW Turbine at 105 m Hub Height. Source: (Sulakshi & Rowland's Work)

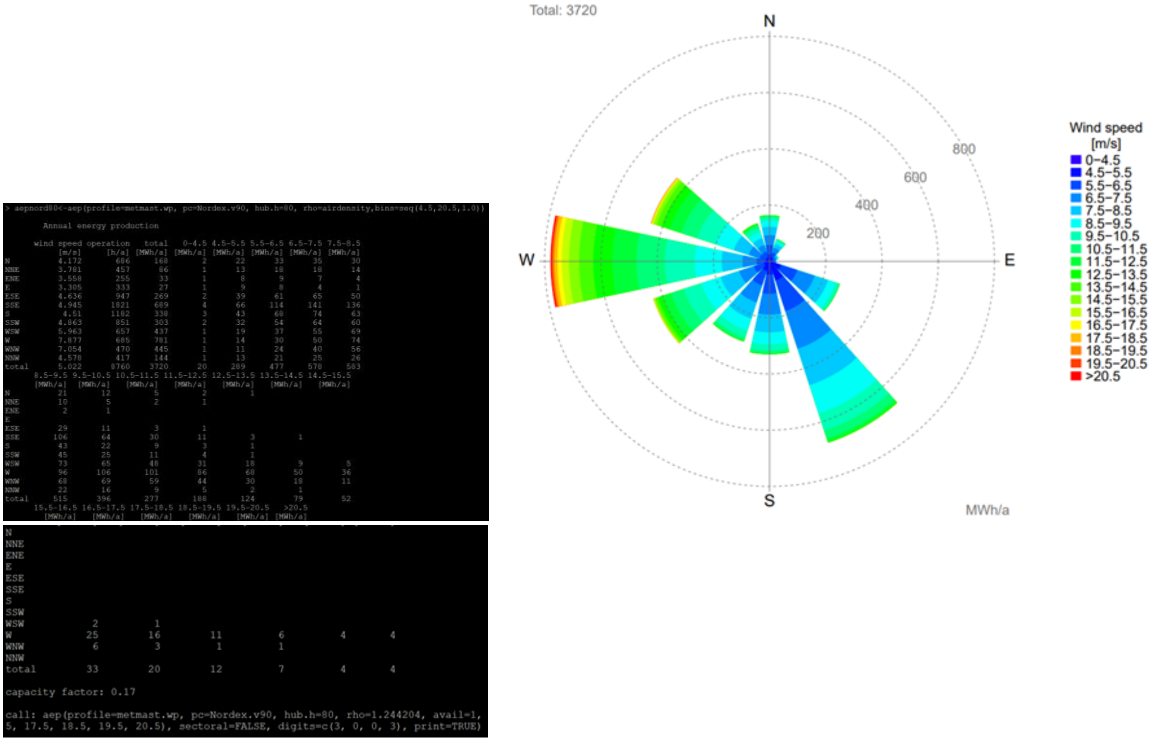


Figure 18: Annual Energy Production for Nordex_N100_2.5MW Turbine at 80 m Hub Height. Source: (Sulakshi & Rowland's Work)

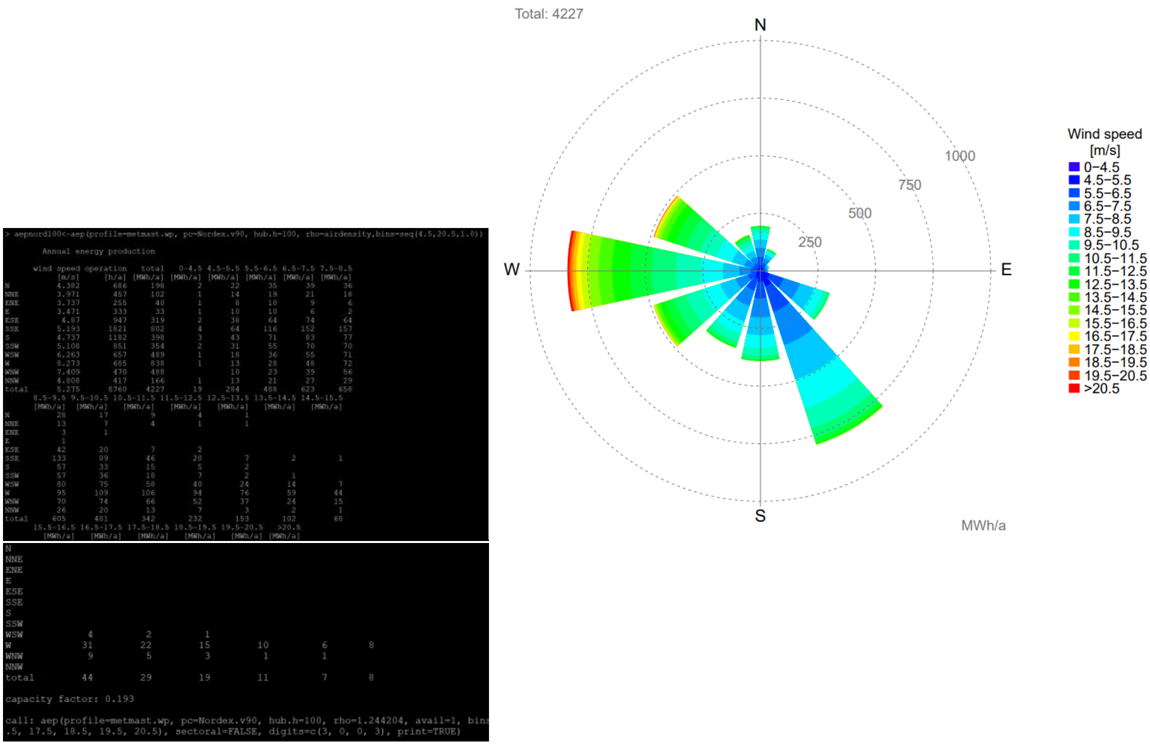


Figure 19: Annual Energy Production for Nordex_N100_2.5MW Turbine at 100 m Hub Height. Source: (Sulakshi & Rowland's Work)

For the same Vestas_v90_3MW turbine at 105 m hub height, the AEP is 3795 MWh/a with highest energy contribution of 807 MWh/a from westerly winds. Most efficient condition for Vestas_v90_3MW is for hub height at 105 m.

For Nordex_100N_2.5MW turbine at 80 m hub height, the highest annual energy of 781 MWh/a generated due to westerly wind flow at a 270^{o} and the highest percentage of this energy produced from 9.5 – 10.5 m/s speed winds. Second highest annual energy of 689 MWh/a generated due to south-south-east windblown at 150 ^{o} angle. Lowest annual energy of 27 MWh/a generated from easterly wind. Total annual energy production for 80 m from Nordex_100N_2.5MW turbine is 3720 MWh/a. At a 100 m hub height of Nordex_100N_2.5MW turbine, the AEP is recorded as 4227 MWh/a. Therefore, by comparing both 80 m, and 100 m hub heights for Nordex_100N_2.5MW, most efficient hub height is 100 m.

By considering both selected turbines as mentioned in table 3, Nordex_100N_2.5MW turbine generated the highest annual energy of 4227 MWh/a at 100 m hub height. Therefore, this turbine is the most efficient annual energy generator at 100 m height.

2.8 Conclusion

Wind speed, wind direction, temperature and pressure data were provided for year 2014 at meteorological site in the Koszalin region. Since the mean wind speeds are relatively low for a wind power project, small wind turbines could be more appropriate for selected Koszalin area. Although the Weibull probability function did not fit the wind speed distributions from most of the directions, the Weibull shape parameters were in line with expectations. The mean wind speed tended to be stronger during the winter season while varying mean wind speed with time of year and the daytime, therefore power output will be higher during these times. Koszalin site wind from western direction exhibited a strong dominant wind, which is beneficial. At Koszalin the terrain is flat and from the wind shear parameters of the power law model, it is clear that the mean wind speed increased with height above ground, as expected.

The annual energy production was calculated and by considering both selected turbines as mentioned in table 3, Nordex_100N_2.5MW turbine generated the highest annual energy of 4227 MWh/a at 100 m hub height. Therefore, this turbine is the most efficient annual energy generator at 100 m height. But other parameters such as turbine intensity, capacity factor of the power plant, analyzing data more than 1 year time period, uncertainty analysis should be considered. In my personal opinion, a small wind turbine could be installed in the Koszalin region, and the actual energy produced should be measured. By measuring the actual energy output of the turbine, the success of the wind resource assessment done for the Koszalin area and the accuracy of predicted values such as capacity factor and annual energy production can be examined.

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Image sources

Satellite Imageries of Sites:
All satellite imageries of sites were obtained from Google Earth imageries

Wind Speed Images; Micro and Meso Scales, Including Power Densities:
European Wind Atlas

Statistics Plots – Histograms, Time Series Power and Energy Plots, and Tables:
All generated from Authors' Analysis.