A Thesis

For the Degree of Master of Engineering

A Study on the Determination Method for Wind Turbine Classes

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Major of Wind Power Mechanical System Engineering
Faculty of Wind Energy Engineering

GRADUATE SCHOOL
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A Study on the Determination Method for Wind Turbine Classes

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Table of Contents

List of Figures

List of Tables

Abstract

Few studies have been conducted on how wind turbine classes are determined when using wind data collected at heights below that of a wind turbine hub. The purpose of this study was to propose an ideal process using such data in order to determine wind turbine class. In this study, an important assumption was made that only one wind turbine was installed at a potential wind farm site, so the wake effect was not considered.

The Measure-Correlate-Predict (MCP) technique was performed to obtain the long-term wind data. Pyeongdae and Gujwa on Jeju Island, South Korea, were selected as the measurement and reference sites, respectively. Consequently, a ten-year period of wind data was generated from one-year measurements.

For extreme wind speed (EWS), the wind shear exponent was analyzed to extrapolate the wind speed at hub height. Also the Gumbel distribution was used as an extreme distribution model and daily maximum wind speed was selected as the extreme data. Estimated extreme wind speed with a return period of 50 years was 43.3m/s at Pyeongdae.

For the turbulence intensity, a new estimation method was proposed to predict the standard deviation of wind speed (SD of WS) at hub height. This method is based on correlation analysis for the SD of WS with the height. The reliability of the method was also confirmed through an accuracy evaluation (showing less than 1% error rate at 15m/s). Estimated average turbulence intensity at 15m/s is 0.10 at Pyeongdae.

As a result, the appropriate wind turbine class at Pyeongdae was class Ⅰ C.

Nomenclature

a	Scale parameter of Gumbel distribution [m/s]
b	Location parameter of Gumbel distribution [m/s]
EPY	Event per year [year^{-1}]
$F(v)$	Gumbel distribution function
I_{ref}	Reference turbulence intensity at 15m/s, dimensionless
R	Correlation coefficient, dimensionless
R^2	Coefficient of determination, dimensionless
T	Return period [year]
TI	Turbulence intensity, dimensionless
V	Wind speed [m/s]
$\overline{V}$	Average wind speed [m/s]
$V_{50}(z)$	Extreme wind speed with a return period of 50 years [m/s]
V_{ref}	Reference wind speed average over 10min [m/s]
Z	Measurement height [m]
Z_{hub}	The wind turbine's hub height [m]
σ	Standard deviation of wind speed [m/s]
σ_I	Representative standard deviation of wind speed [m/s]
$\overline{\sigma}$	Average standard deviation of wind speed [m/s]
σ_σ	Standard deviation of σ [m/s]
γ	Wind shear exponent (Power law exponent), dimensionless

1. Introduction

1.1 Background

The importance of incorporating safety in design is emphasized in many areas. The wind energy engineering field also tries to design wind turbines which are safe in any environment. The design requirements for wind turbines are provided in the international standard 61400-1 ed.3. Many wind turbine manufactures refer to this standard to secure the safety [1].

In designing wind turbines, analysis of external conditions is necessary in order to ensure the level of safety and reliability meets industry standards. Among said external conditions, the wind condition is the most important factor in design. In particular, the IEC 61400-1 standard requires extreme wind speed (EWS) and turbulence intensity data for determining the appropriate wind turbine class.

The IEC 61400-1 standard considers different wind cases including the extreme conditions [1]. EWS poses a special case in design process, due to its infrequent occurrence. However, EWS puts a severe mechanical load on the wind turbines and can lead to dangerous situations. Accordingly, the wind turbines should be designed to withstand these extreme conditions [2].

Wind changes frequently, but more so in cases where it passes over rough surfaces or around obstacles like buildings, mountains and trees. These changes cause turbulence, and turbulence intensity is its basic measure. It represents the atmospheric stability. High turbulence reduces energy output and has an impact on the load, wear, and operation of the wind turbines [3]. Therefore, a careful analysis of the EWS and turbulence intensity should be done to determine the wind turbine class suitable for the potential wind farm sites.

1.2 Objectives

Determination of the wind turbine class is important to secure the structural stability of the wind turbines. In the international standard IEC 61400-1 ed.3, wind turbines classes are classified in terms of the two parameters, extreme wind speed (EWS) and turbulence intensity [1].

The purpose of this study is to propose a process for determining wind turbine class based on the IEC standard. In addition, an ideal method was considered for estimating wind turbine classes, using wind data measured at a height below the hub height, i.e. below an assumed hub height of 80 meters.

The onsite effective turbulence intensity should be estimated factoring in the wake effect behind turbines. However, this study made an important assumption that only one wind turbine was installed at a potential wind farm site. Therefore, the wake effect was not considered.

1.3 The method of study

Figure 1 explains the process. Here, the H.H, SD of WS and AVG represent the hub height of wind turbines, standard deviation of wind speed and average, respectively. The wind turbine class can be determined by analyzing the EWS and turbulence intensity at a potential site.

For estimating the EWS, first, perform the MCP (Measure-Correlate-Predict) technique to gain long-term wind data. Second, predict hub height wind speed based on the method for extrapolating wind speed at the required height, using the wind shear exponent. Third, extract the extreme data from the long-term wind data. In this step, it is important what type of extreme data would be used. Daily maximum wind speed (DMWS) was used in this study. Fourth, estimate the hub height EWS. In particular, onsite EWS with a return period of 50 years is required for determining wind turbine class.

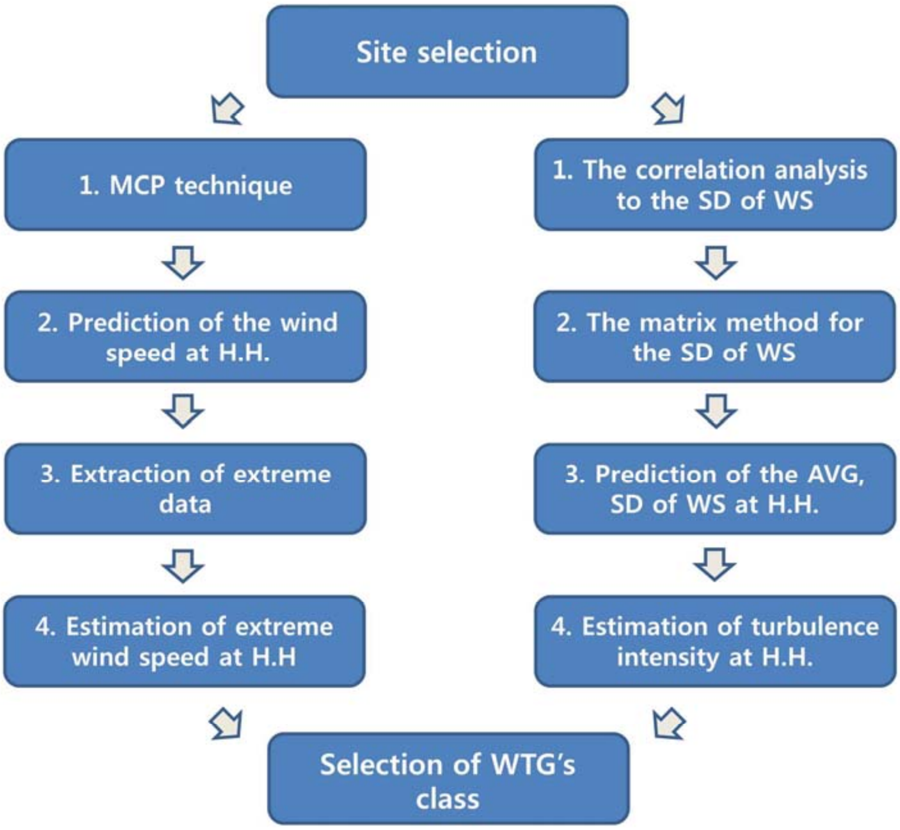


Fig. 1. Process for determining the wind turbine class.

The turbulence intensity is defined as the ratio of the standard deviation to the average, so the standard deviation of wind speed is necessary for calculating turbulence intensity. However, wind data usually are measured at a height lower than that of the wind turbine hub due to financial and technical problems. As the measurement height increases, it needs more money and higher technical skills. Therefore, the actual turbulence intensity at hub height is unknown. To solve this problem, an estimation of the SD of WS at a different height is needed, but few studies have been conducted in this research area. Therefore, a new method for estimating the SD of WS with the height was proposed in this study.

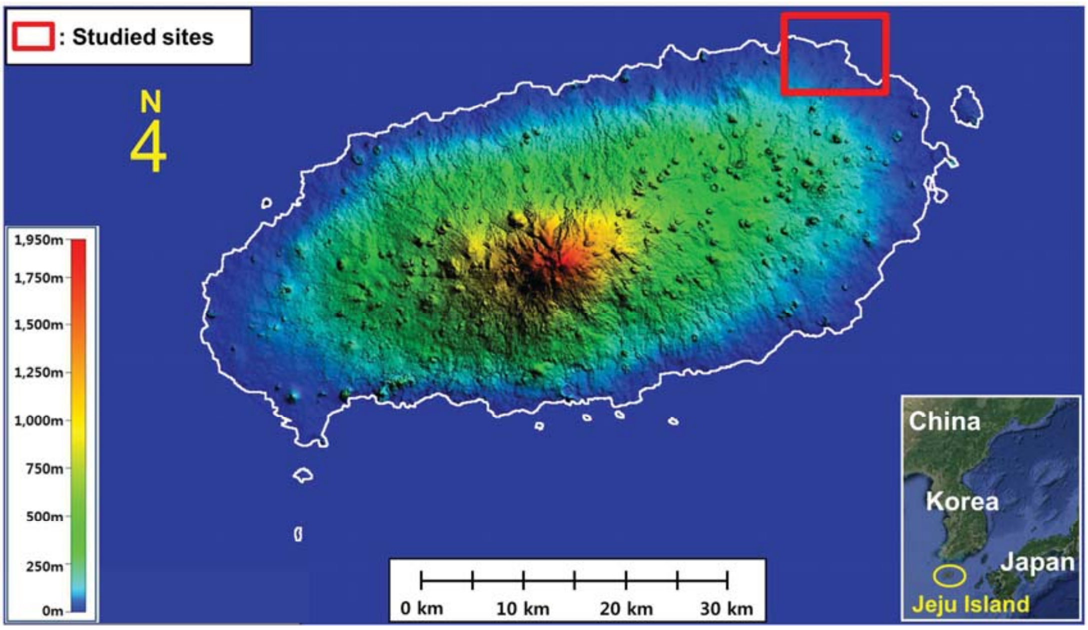
For estimating the turbulence intensity, the following process is conducted. First, perform a correlation analysis of the SD of WS with the measurement height at each wind speed bin and at each directional sector, respectively. Second, the matrix is made for the SD of WS at hub height with the wind speed. Then, the matrix is applied to time-series real wind data. Third, estimate the average and standard deviation of wind speed at hub height using the wind shear exponent and the matrix, respectively. Fourth, calculate the turbulence intensity at hub height using the estimated figures above.

Finally, compare the estimated EWS and turbulence intensity with the reference wind speed, V_{ref}, and reference turbulence intensity, I_{ref}, which are provided in the IEC standard for wind turbine classification. In the end, an appropriate wind turbine class is determined for the site.

2. Sites and wind data

2.1 Site descriptions

Figure 2 shows the location of the research sites. Jeju Island is located off the southern coast of the Korean peninsula, at a latitude of 33°06' ~ 34°00' north and a longitude of 126°08' ~ 126°58' east, as shown in the small figure at the lower right corner of Figure 2(a). Jeju Island has an area of 1,849.2㎢ including a length, approximately 73㎞ from east to west and 41㎞ from north to south. It is a volcanic island and 1,950m-high Halla Mountain is located at its center. As shown in Figure 2(a), Jeju Island has various topographical conditions, from the mountainous to the coastal areas.



(a) Digital terrain map of Jeju Island

(b) Aerial photo of the studied sites

Fig. 2. Location of the studied sites.

Pyeongdae and Gujwa are situated at the northwestern coast of the Island. The distance between the two sites is about 1㎞. There is a small village between two sites which is called Sehwa-ri. The village has an area of 19,284㎡ and a population of 1,960 residents. Since there are no high buildings or obstacles to interrupt the wind flow, the village does not have much effect on the wind condition at the sites.

2.2 Sites, measurement conditions and wind sensors

Since Pyeongdae and Gujwa are located near the sea, typical sea-surface appears at the sites. Sea-surface wind generally shows high speed due to no obstacles [4]. Pyeongdae and Gujwa also showed similar wind characteristics in the previous investigation.

Table 1 shows sites and measurement conditions. Pyeongdae is a site with a 60m-high met mast while Gujwa is a site with a 14m-high AWS (Automatic Weather System). As for the meteorological equipment, an AWS can observe the weather condition for a long-term period controlled by the Korea Meteorogical Service. Also the wind condition was generally measured by AWS wind sensors at 10~14m height. On the other hand, Pyeongdae and Gujwa are the low altitude areas at 19 and 25m, respectively.

Table 1 Sites and measurement conditions.

Sites	Pyeongdae	Gujwa
Longitude	126°50'31"E	126°51'6"E
Latitude	33°31'33"N	33°31'21"N
Altitude [m]	19	25
Measurement period	7 Feb 2010- 6 Feb 2011	1 Jan 2003- 31 Dec 2015
Height of anemometer [m]	60, 59, 50, 40, 30	14
Height of wind vane [m]	60, 40	14
Recovery rate [%]	100	99.6
Average wind speed[m/s]	7.22@60m	4.01@14m
Prevailing wind direction	NNW	WNW/NNW
Type	Measurement site	Reference site

The heights of the anemometers at Pyeongdae are 60, 59, 50, 40 and 30m while those of the wind vanes are 60 and 40m, respectively. But the heights of the anemometer and the wind vane at Gujwa are equal at 14m. All wind data recordings occurred at 10-min averaged intervals.

The wind data at Pyeongdae was measured for 1 year and showed an average wind speed of 7.22m/s at 60m height and a prevailing wind direction of NNW. Meanwhile, the wind data at Gujwa was measured for 10 years and showed an average wind speed of 4.01m/s at 14m height with a prevailing wind direction of NW.

Table 2 lists the specifications of wind sensors on a met mast and an AWS.

Table 2 Specifications of the wind sensors on met mast and AWS.

Items	Met mast at Pyeongdae		AWS at Gujwa	
	Anemometer	Wind vane	Anemometer	Wind vane
Model	NRG #40	NRG #200P	WM-Ⅳ-WS	WM-Ⅳ-WD
Type	3-cup	Potentiometric	3-cup	Potentiometric
Measuring range	1-96 [m/s]	0-360 [deg]	0-70 [m/s]	0-360 [deg]
Accuracy	5-25 m/s: <0.1 m/s	<1%	0-10 m/s: <0.3 m/s Over 10 m/s: <3%	<±5°
Threshold	0.78 m/s	1 m/s	0.3 m/s	0.5 m/s

2.3 Wind characteristics

Figure 3 shows a comparison of the observed wind speed distributions at two sites with the fitted Weibull distributions. Two Weibull parameters for shape, k, and scale, c, are also presented in the Figure. Pyeongdae showed higher values of two Weibull parameters than Gujwa. In addition, Pyeongdae showed high frequency in the high speed range, while Gujwa showed high frequency in the low wind speed range, possibly owing to the difference in measurement heights. Figure 4 shows the monthly wind speed at these sites. Two sites showed the highest wind speed was in winter and the lowest wind speed was in summer. It is typical for Jeju Island, where the winter monsoon has great influence; strong wind blows in this season.

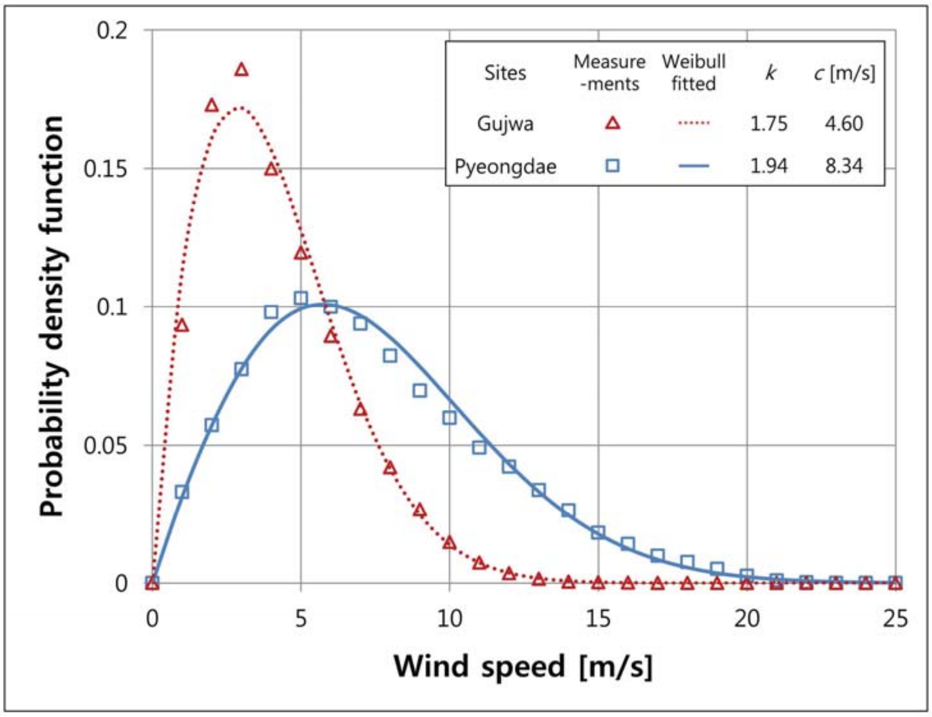
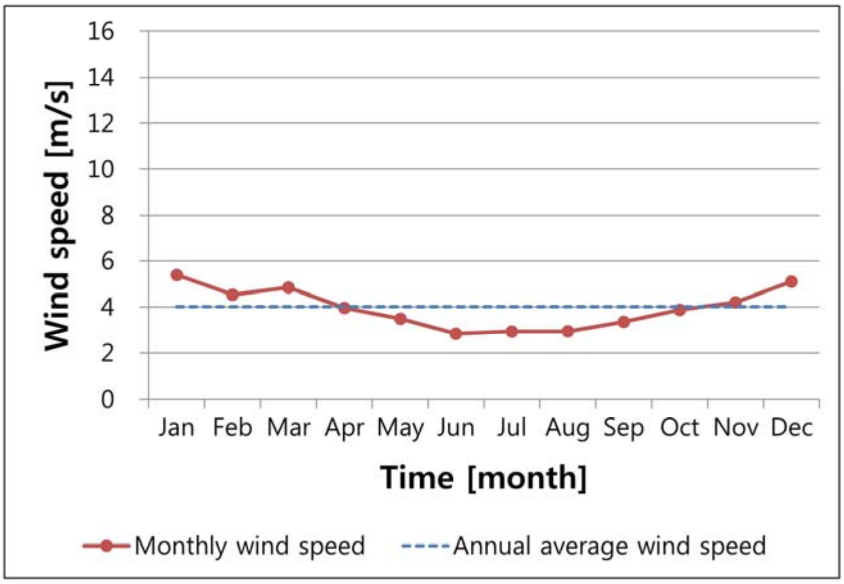
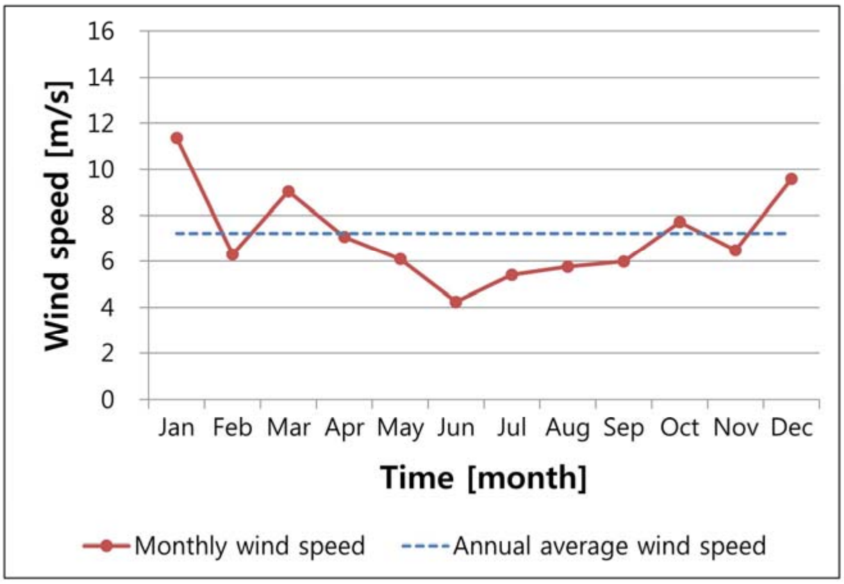


Fig. 3. Comparison of the wind speed distribution at the sites (Height: 14m at Gujwa, 60m at Pyeongdae).



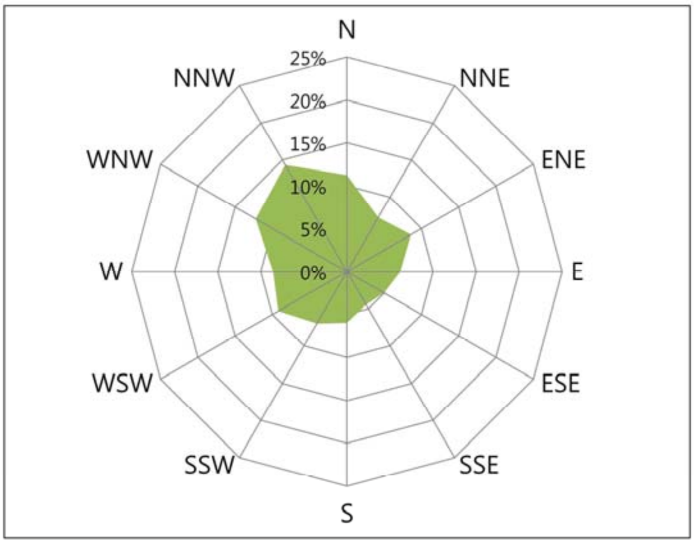
(a) Gujwa (10 years)



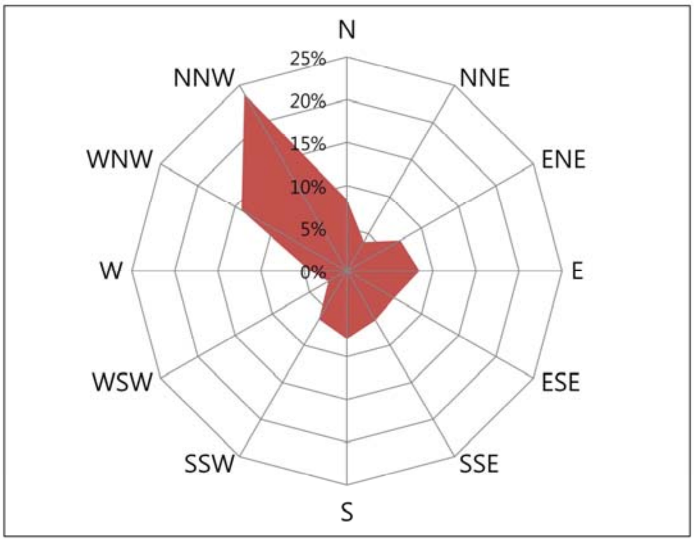
(b) Pyeongdae (1 year)

Fig. 4. Monthly wind speed.

Figure 5 shows the directional wind frequency at the sites. With regard to the prevailing wind direction, the wind direction at Pyeongdae is even more biased toward NNW than Gujwa. Considering that the distance between the two sites is very short (1㎞) this result may be due to the difference in the measurement heights, not a topographical condition. For applying the MCP (Measure-Correlate-Predict) technique, Pyeongdae and Gujwa were selected as the measurement and reference sites, respectively.



(a) Gujwa (10 years)



(b) Pyeongdae (1 year)

Fig. 5. Wind direction frequency.

2.4 Data validation

Data validation is necessary to obtain reliable results, and should be performed before analyzing wind data. Data validation was generally performed by using three measurement data tests; range test, relation test, trend test [5, 6]. The data showing significant errors in these tests was eliminated.

In addition, wind data affected by typhoons were not considered in this study. The IEC standard 61400-1 states that wind conditions experienced in tropical storms such as hurricanes, cyclones, and typhoons are not considered to determine wind turbine class [1]. Thus, the wind data for two days affected by two typhoons which were named MAEMI(2003) and NARI(2007) were excluded in this work. These two typhoons known as big typhoons directly affected Jeju Island, causing great damage with very high wind speeds. Table 3 indicates excluded extreme wind values due to the typhoons. In the table, DMWSs are arranged in descending order and the top two wind speeds affected by typhoons were excluded.

Table 3 Excluded wind data (Height: 80m, Site: Pyeongdae).

Date	Daily maximum wind speed [m/s]	Typhoon	Results
2003-09-12	50.9	MAEMI	Excluded
2007-09-16	47.6	NARI	Excluded
2012-08-27	35.2	-	-
2011-08-07	34.7	-	-
2012-08-28	34.2	-	-
2012-09-17	30.8	-	-
2004-09-07	30.6	-	-
2004-07-04	30.6	-	-
2006-04-20	29.3	-	-
2004-02-22	29.1	-	-
…	…	…	…

3. The method for determining wind turbine class

3.1 Wind turbine classes on IEC 61400-1

The international standard IEC 61400-1 ed.3 classifies wind turbines according to the reference wind speed, V_{ref}, and reference turbulence intensity, I_{ref}, at the wind turbine's hub height. Table 4 shows basic parameters for wind turbine classes provided by the standard.

Figure 6 shows representative values of the turbulence standard deviation, σ_1, and the turbulence intensity, σ_1/V_{hub}, for the given hub height wind speed, based on the reference turbulence intensity.

Table 4 Basic parameters for wind turbine classes (Source: IEC 61400-1, ed.3).

Wind turbine class	I	Ⅱ	Ⅲ	S
V_{ref} [m/s]	50	42.5	37.5	Values specified by the designer
A, I_{ref}	0.16			
B, I_{ref}	0.14			
C, I_{ref}	0.12			

<The parameter values apply at the hub height>

V_{ref} : the reference wind speed average over 10min

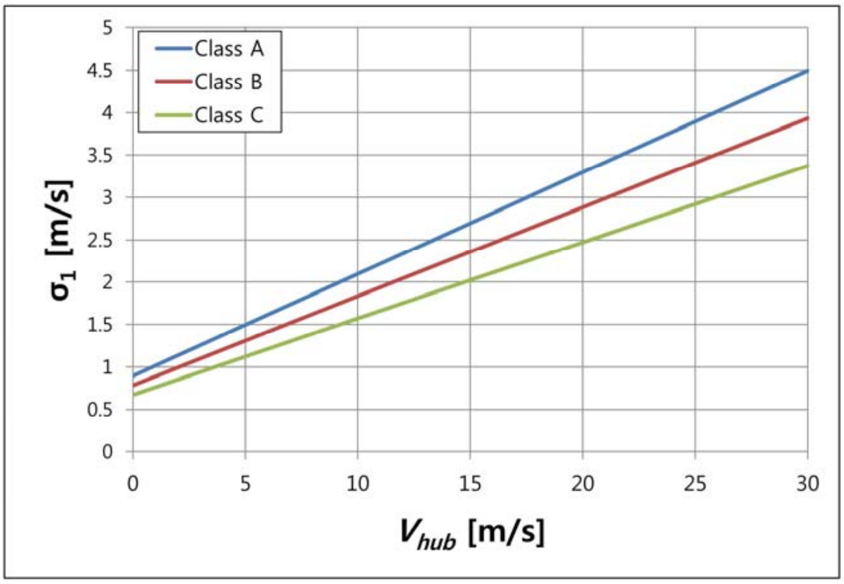
A : designates the category for higher turbulence characteristics

B : designates the category for medium turbulence characteristics

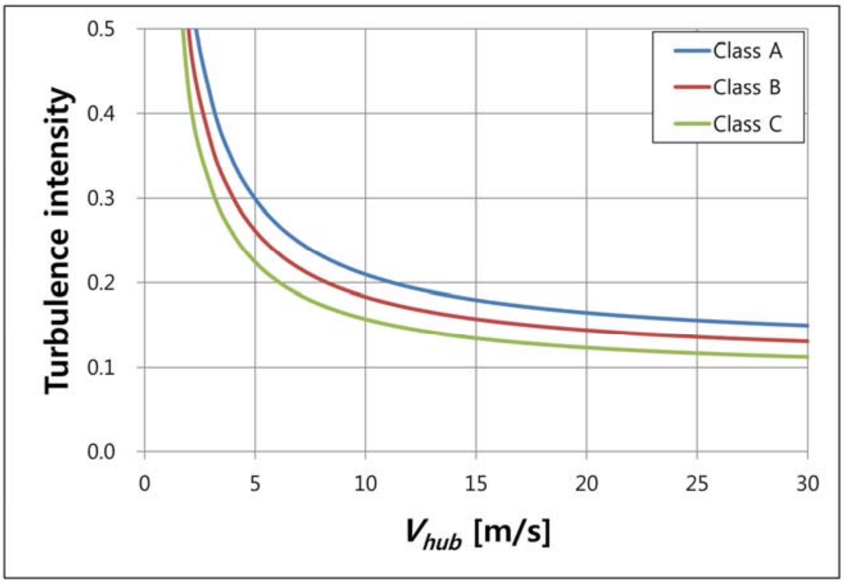
C : designates the category for lower turbulence characteristics

I_{ref} : the expected value of the turbulence intensity at 15 m/s

(Note: I_{ref} is defined as the mean value rather than as a representative value)



(a) Turbulence standard deviation



b) Turbulence intensity

Fig. 6 Representative turbulence standard deviation and turbulence intensity for the normal turbulence model (NTM).

The onsite effective turbulence intensity should include the wake effect behind wind turbines [1, 3]. However, the wake effect is not considered in this work since this study assumes that only one wind turbine was installed at a potential wind farm site. So turbulence at the site is only caused by ambient wind conditions without respect to the wake effect. On the other hand, in complex terrain, the turbulence intensity should be multiplied by a correction factor [1].

A correction factor was also considered in this work because the Pyeongdae site is not complex terrain. Roughness length is normally used to classify the terrain condition. Table 5 presents terrain surface characteristics according to Roughness class and Roughness length, and Wind shear. Roughness length at Pyeongdae is 0.0214m; this value belongs to the open terrain with a smooth surface. It means that Pyeongdae is a flat terrain, not a complex one.

A specific wind turbine class can be determined if the following requirements are satisfied [1];

① Onsite EWS with a return period of 50 years is less than a specific wind turbine class's V_{ref}.

② Onsite turbulence intensity is less than a specific wind turbine class's I_{ref}. The onsite turbulence intensity is mainly taken into account in the range from 0.6 times the rated wind speed to cut-out wind speed of the wind turbine.

Table 5 Terrain surface characteristics.

Description	Roughness Class	Roughness Length [m]	Wind Shear
Open sea	0	0.0001-0.003	0.08
Open terrain with a smooth surface, like concrete runway, mowed grass	0.5	0.0024	0.11
Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills	1	0.03	0.15
Agricultural land with some houses and 8-m-tall sheltering hedgerows with a distance of approx. 1,250m	1.5	0.055	0.17
Agricultural land with some houses and 8-m-tall sheltering hedgerows with a distance of approx. 500m	2	0.1	0.19
Agricultural land with many houses, shrubs and plants, or 8-m tall sheltering hedgerows with a distance of approx. 250m	2.5	0.2	0.21
Village, small towns, agricultural land with many or tall sheltering hedgerows, forests, and very rough and uneven terrain	3	0.4	0.25
Larger cities with tall buildings	3.5	0.8	0.31
Very large cities with tall buildings and skyscrapers	4	1.6	0.39

(Source: EMD[1])

1) WindPRO: Software and User Manual, Available through EMD International A/S, www.emd.dk

3.2 Analysis of extreme wind speed

To estimate EWS, the Gumbel distribution composed of the extreme data is normally used [7, 8 ,9]. Also, it is recommended that the extreme data be collected from the long-term wind data. This is because wind measurement data for a few years cannot represent the wind climate for the life of the wind turbines (typically, 20 years). The MCP (Measure-Correlate-Predict) technique was considered when generating the long-term wind data. The daily maximum wind speed (DMWS) data were used as the extreme data because it was the best choice for estimating EWS [10].

3.2.1 MCP (Measure-Correlate-Predict) application

Generally, met masts lower than the wind turbine's hub height are installed to measure the wind condition. The met mast operates for just a few years due to the limited cost, the environmental effects and the short lifespan of wind sensors. Wind measurements for a few years cannot provide enough information on the wind condition for the lifetime of the wind turbine. To estimate an exact EWS, long-term wind data are required, and the MCP technique can be a solution. MCP technique is one of the more popular ways to convert a short-term wind data to a long-term one. For MCP technique, the steps are as follows [3].

① **Measure**: Collect onsite measurement data and neighboring long-term reference data sets.

② **Correlate**: Calculate correlation coefficient between onsite measurement data and long-term reference data sets for the concurrent time period. Determine the proper long-term reference data for estimating wind speed with an acceptable correlation coefficient.

③ **Predict**: Obtain the transfer function between the concurrent wind data. Then, estimate the wind speeds for the duration of the reference time-series data using the transfer function.

Prediction is the most important step in MCP technique and many types of MCP techniques have been developed for the prediction such as Regression, Weibull Parameter Scaling and Matrix method [11, 12, 13].

For MCP application, 60m-high met mast data at Pyeongdae were designated as the onsite measurement data while 14m-high AWS data at Gujwa were designated as the reference data. In addition, the Regression method was selected for the prediction because it is widely used in many research areas.

3.2.1.1 Prediction of the wind speed

A linear regression method was applied to wind speed estimation. This method characterizes the relationship between the measurement and reference data, linearly, in the following [3]:

$$Y = aX + b \tag{1}$$

where X and Y are the wind speeds from the reference and onsite data, respectively. The regression parameters, a and b, are calculated using a least squares method.

Table 6 shows the statistics of a linear regression at two sites. The wind direction was divided into 12 sectors with an angle of 30 degrees because the division of the wind direction raises the accuracy of the prediction [14, 15]. The average value of correlation coefficient, R, is 0.92.

Table 7 shows the quality of reference data according to correlation coefficient. If correlation coefficient is more than 0.80, the quality of reference data is generally considered to be good for the MCP application as shown in Table 7 [16]. Therefore, the AWS data at Gujwa are suitable for reference data. The sector of NNW showed the highest value of correlation coefficient, 0.96 while the sector of WSW showed the lowest value, 0.54. This may result from different topographical conditions which lead to different wind conditions.

Table 6 The statistics of a linear regression at Pyeongdae and Gujwa.

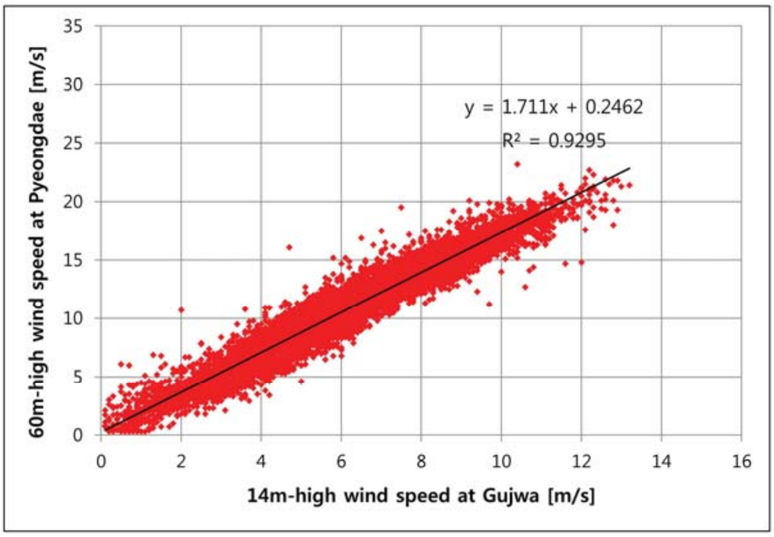
Sector [deg]	Number of data	Slope	Intercept	*R*
N (345-15°)	1,874	1.70	-0.26	0.94
NNE (15-45°)	2,712	1.73	-0.38	0.94
ENE (45-75°)	4,787	1.73	-0.21	0.92
E (75-105°)	2,999	1.95	0.57	0.90
ESE (105-135°)	2,146	1.88	1.07	0.86
SSE (135-165°)	2,972	1.62	1.62	0.90
S (165-195°)	4,766	1.45	1.67	0.89
SSW (195-225°)	4,631	1.39	1.66	0.85
WSW (225-255°)	4,987	1.24	0.79	0.54
W (255-285°)	4,352	1.53	1.88	0.91
WNW (285-315°)	8,175	1.72	1.14	0.94
NNW (315-345°)	7,955	1.71	0.25	0.96
Total/Avg.	52,356	-	-	0.92

Table 7 Quality of reference data for MCP application.

Correlation coefficient	Quality of reference data
0.5-0.6	Very pool
0.6-0.7	Poor
0.7-0.8	Moderate
0.8-0.9	Good
0.9-1.0	Very good

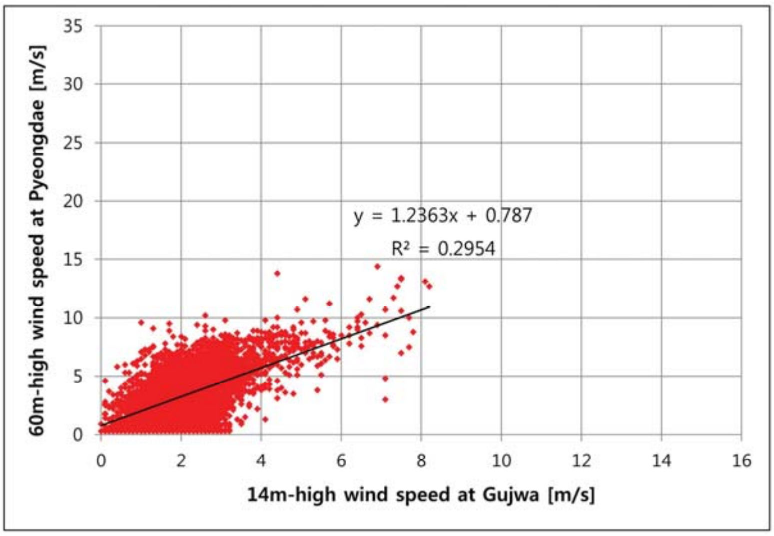
(Source: EMD)[2)]

Linear regression graphs for these two sectors are shown in Figure 7. The R^2 in the figure is the coefficient of determination. Since the higher value of R^2 means that the straight line is fitted more closely to the scattered data, the sector with the higher value of R^2 shows a better condition for the prediction [17, 18].



(a) Sector: NNW (315 - 345°)

2) WindPRO: Software and User Manual, Available through EMD International A/S, www.emd.dk



(b) Sector: WSW (225 - 255°)

Fig. 7. Linear regression of wind speed at Pyeongdae and Gujwa.

Table 8 shows a comparison between the observed and MCP predicted wind speeds during the concurrent period from February 2010 to February 2011 (1 year). It is confirmed that the predicted values are similar to observed values. Thus, the MCP technique is applicable to obtain the long-term wind data for the other period of time at reference wind data.

Figure 8 shows the result of the MCP prediction. In addition to two observed wind speeds which are based on the measurement and reference data, the MCP predicted wind speed is also compared during the concurrent period. It is confirmed that there is little difference between the observed and predicted wind speeds.

Table 8 Comparison between the observed and MCP predicted wind speeds (Height: 60m).

Parameters	Measurement	MCP
Average [m/s]	7.22	7.22
Median [m/s]	6.60	6.47
Mode [m/s]	5.30	4.00
Range [m/s]	23.00	22.83
Standard deviation [m/s]	4.09	3.84
Variation coefficient [%]	56.72	53.16
Skewness	0.65	0.81
Kurtosis	0.01	0.23

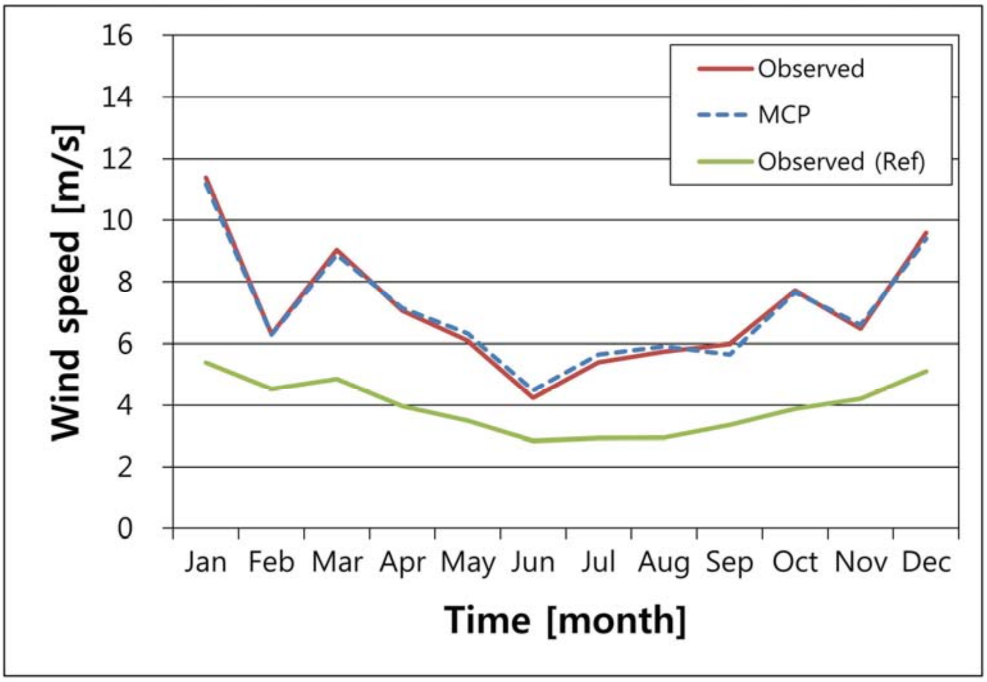


Fig. 8. Comparison between the observed and MCP predicted wind speeds.

3.2.1.2 Prediction of the wind direction

The wind veer was taken into account for wind direction estimation. The wind veer is defined as the difference between the two concurrent wind directions which were observed at different sites. Wind direction is generally estimated using a regression method in the following form [3]:

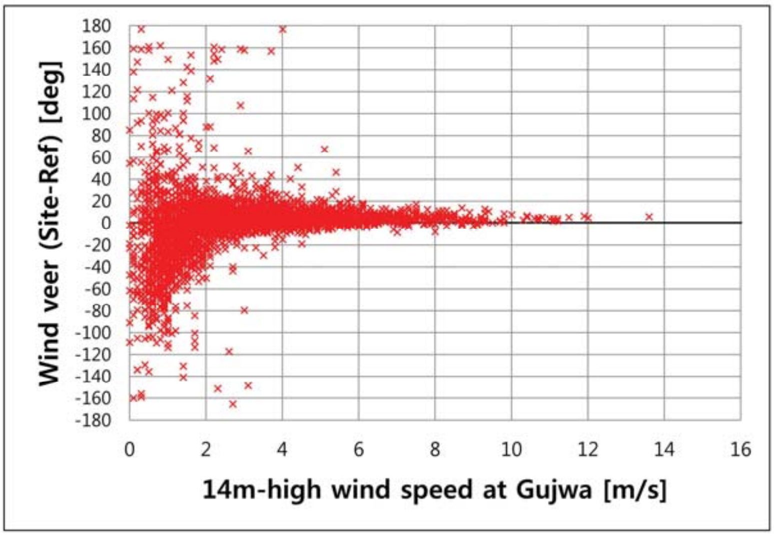
$$Y = X + c \tag{2}$$

where X and Y are the wind direction from the reference and onsite data, respectively. The regression parameter, c, is the average value of the wind veer. Table 9 shows the constant, c, sector-by-sector.

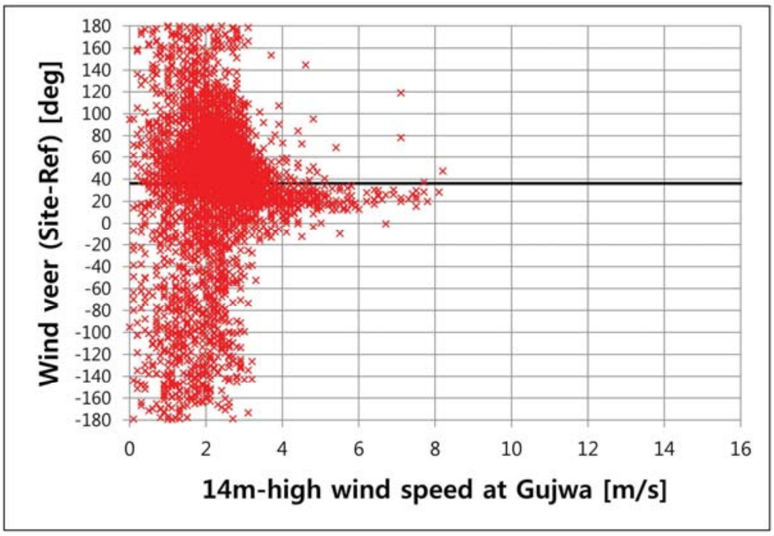
Table 9 The regression parameter of wind direction.

Sector	Constant
N	2.04
NNE	3.33
ENE	11.87
E	11.11
ESE	7.34
SSE	-1.70
S	0.38
SSW	3.37
WSW	36.15
W	29.31
WNW	16.81
NNW	15.13

Figure 9 shows the wind veer for the two sectors of the S and WSW. These two sectors were selected as the representative for all directional sectors. That is because the sector of S showed the lowest value of constant, 0.38, while the sector of WSW showed the highest value, 36.15.



(a) Sector: S (165 - 195°)



(b) Sector WSW (225 - 255°)

Fig. 9. Regression of wind direction at Pyeongdae and Gujwa.

Figure 10 shows a comparison between the observed and predicted wind direction frequency during the concurrent period. It is also confirmed that the observed wind direction frequency is very similar to the MCP predicted wind direction frequency.

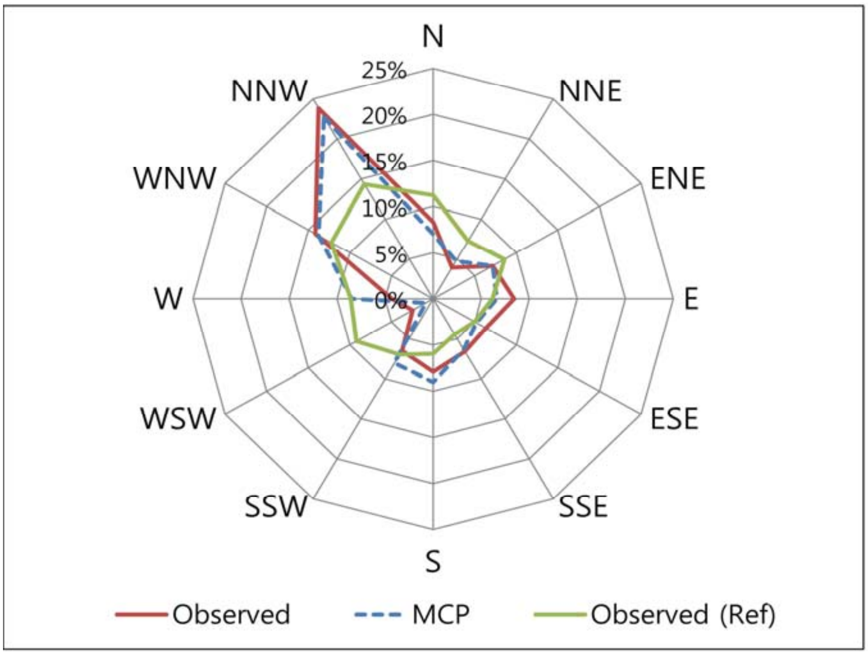


Fig. 10. Comparison between the observed and MCP predicted wind directions.

3.2.2 Estimation of the wind speed at the hub height

In the previous step, the long-term data for 10 years were obtained using the MCP technique, but these are 60m-high wind data. Since wind data at hub height are required to determine the wind turbine class, the wind data should be used to extract wind data fitted to hub height assumed to be 80m in this study.

In general, wind speed increases with height. Wind shear means the variation of wind speed as a function of height. The power law method is commonly used to represent wind shear and it can be calculated in the following equation [2, 3, 19]:

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\gamma} \tag{3}$$

where V_1 and V_2 are the average wind speed at heights of Z_1 and Z_2. γ is called the power law exponent or wind shear exponent.

The wind shear exponent can be calculated using a linear least-squares regression [20, 21, 22]. Taking a natural logarithm in Equation (3), the following equation is obtained:

$$\ln\left(\frac{V_2}{V_1}\right) = \gamma \cdot \ln\left(\frac{Z_2}{Z_1}\right) \tag{4}$$

Here, a straight line which should be passed by (0,0) can be drawn through $\ln(Z_2/Z_1)$ on the x-axis and $\ln(V_2/V_1)$ on the y-axis. Wind shear exponent is the slope of the straight line.

The wind shear exponent was analyzed in this work considering the division of wind direction. The result is indicated in Table 10. The table shows the average wind speed at each measurement height and wind shear exponent according to the wind direction. The R^2 is the coefficient of determination which means how well the data fit a linear regression model.

Since the wind data from the met mast have been collected at different measurement heights, the ratio of wind speed and the ratio of the height in Equation (4) should be calculated at different heights, respectively [23, 24, 25]. Then, the wind shear exponent can becomputed using a least squares regression. As for the wind data at Pyeongdae, it had been measured from 60, 59, 50, 40 and 30m heights. However, the wind speed data at a 59m height was not used because 59m is very close to 60m.

Finally, the wind data at 80m hub height were estimated using the wind shear exponent in Table 10 and Equation (3).

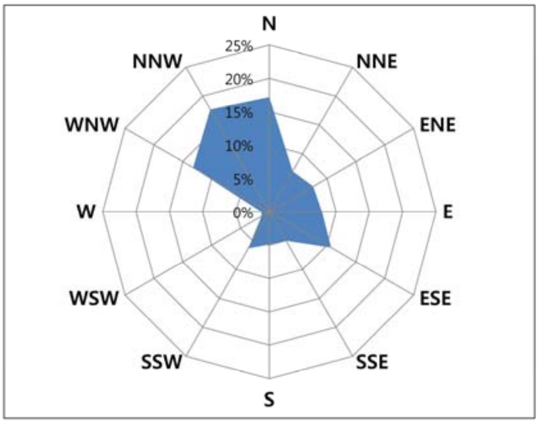
Table 10 The statistics of the wind shear exponent.

Sector	Average wind speed [m/s]					R^2	Wind shear exponent	Number of data
	H:60m	H:59m	H:50m	H:40m	H:30m			
N	8.08	8.09	8.07	7.95	7.91	0.79	0.034	4,393
NNE	5.19	5.21	5.14	5.11	5.04	0.89	0.045	2,063
ENE	6.93	6.98	6.86	6.75	6.59	0.94	0.078	3,765
E	6.72	6.24	6.38	6.35	5.94	0.11	0.116	4,439
ESE	5.54	5.32	5.09	4.88	4.75	0.45	0.202	3,330
SSE	5.83	5.81	5.57	5.40	5.08	0.98	0.196	3,480
S	6.01	6.00	5.70	5.49	5.16	0.97	0.219	4,164
SSW	6.95	6.94	6.63	6.35	5.90	0.99	0.236	3,411
WSW	5.21	5.15	4.98	4.77	4.45	0.99	0.221	1,301
W	4.77	4.70	4.50	4.28	3.98	0.98	0.253	2,252
WNW	6.80	6.76	6.49	6.31	5.93	0.97	0.191	7,434
NNW	9.74	9.71	9.53	9.35	9.17	0.95	0.088	12,528
Avg./Total	7.22	7.15	6.98	6.82	6.56	0.96	0.132	52,560

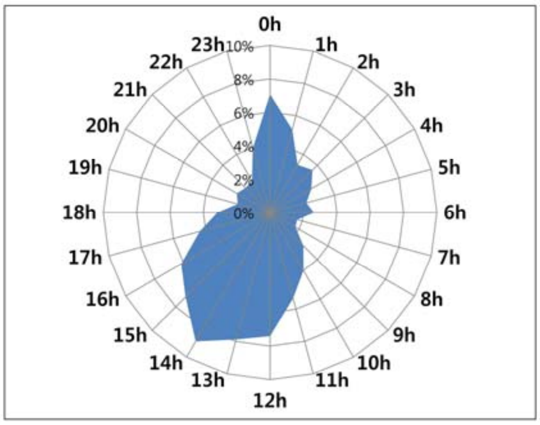
3.2.3 Extraction of extreme data

The extreme distributions are required to estimate the EWS and it is composed of many extreme data. Thus, the extreme data should be collected before forming the extreme distribution. For the extreme data, this study used DMWSs extracted from the estimated 80m-high time-series wind data for 10 years.

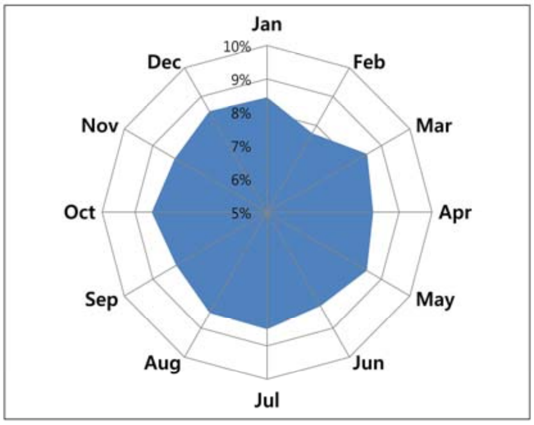
Figure 11 shows the occurrence frequency of the DMWS according to direction and time. The DMWS at Pyeongdae mainly occurred in the northwest of 315° to 360° and in the time of 13:00 to 15:00. There is not a big difference in the seasonal variation.



(a) Directional occurrence frequency



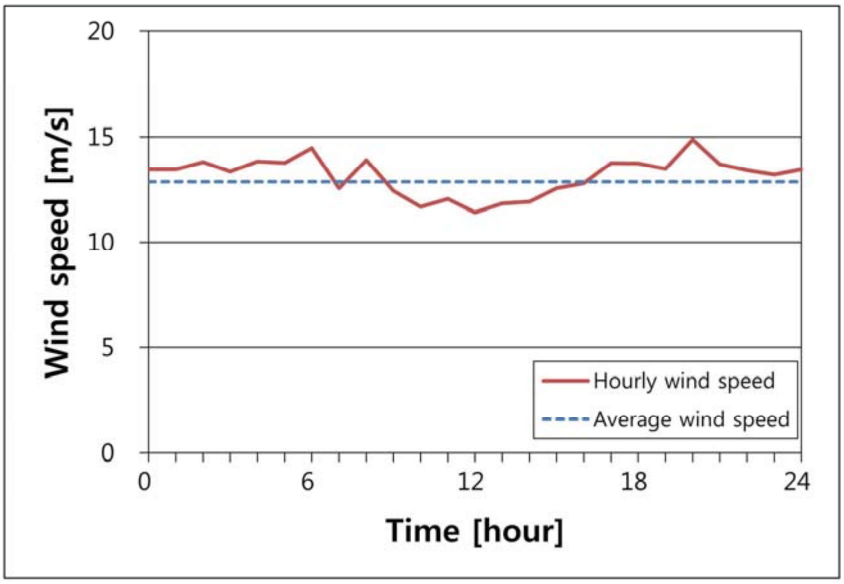
(b) Diurnal occurrence frequency



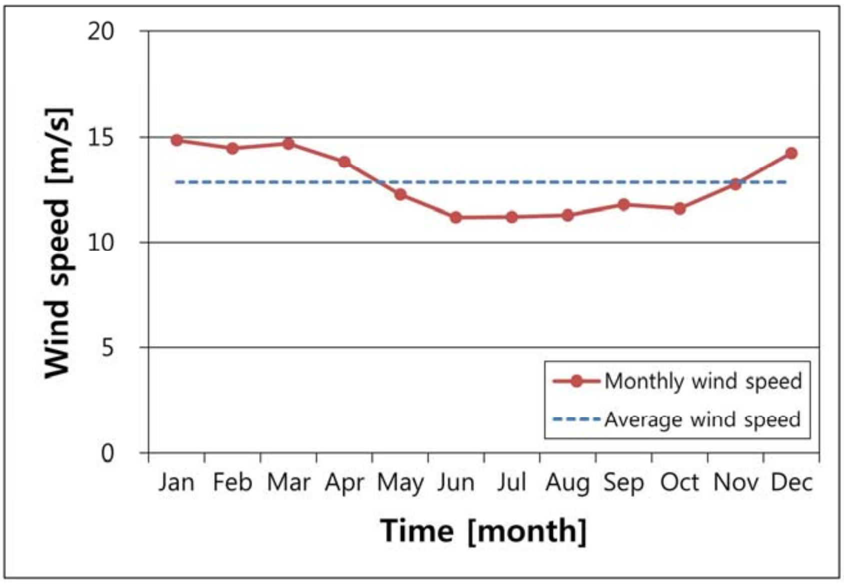
(c) Seasonal occurrence frequency

Fig. 11. Occurrence frequency of the DMWS.

Figure 12 shows the wind speed variation of the DMWS. The DMWS at Pyeongdae showed the highest wind speed occurred during the winter but there is not a big difference in the diurnal variation.



(a) Diurnal wind speed variation



(b) Monthly wind speed variation

Fig. 12. Wind speed variation of DMWS.

3.2.4 Estimation of extreme wind speed at the hub height

The Gumbel distribution has been commonly used as an extreme distribution model in many research areas, including wind energy. The cumulative probability distribution function, *F(v)*, of the Gumbel distribution is the following equation [2, 3, 7]:

$$F(v) = \exp\left[-\exp\{-a(v-b)\}\right] \tag{5}$$

where v is extreme wind value, a is a scale parameter, and b is a location parameter, which are given by the following equations [26]:

$$a = \frac{\pi}{\sigma\sqrt{6}} = \frac{1}{0.78\sigma} \tag{6}$$

$$b = \overline{v} - 0.45\sigma \tag{7}$$

Here, $\overline{v}$ is the average of a set of extreme wind values, and σ is the standard deviation of the set. In addition, by modifying Equation (5), the EWS is given by

$$EWS = -\frac{1}{a}\ln\left[-\ln F(v)\right] + b \tag{8}$$

Areas of research investigating phenomena such as earthquakes, floods and mechanical defect have tried to estimate the likelihood of events during specific periods [9, 27, 28]. For this reason, a return period should be considered. A return period is called as a recurrence interval and it means the event only occurs once for a return period. To apply a return period to the Gumbel distribution, it is assumed that Equation (5) is the annual probability and an event which has occurred once in n years has the annual probability of recurrence equal to $1/n$. Therefore, EWS, which has the return period, T years, recurs with annual probability of $1/T$ and the annual probability that is less than or equal to

EWS is as follows [3, 9]:

$$\mathrm{Prob}(EWS,\ T) = 1 - \left(\frac{1}{T}\right) \tag{9}$$

If a number of extreme wind values appear within years, the probability can be expressed using the event per year, *EPY*, as the following:

$$\mathrm{Prob}(EWS,\ T) = 1 - \left(\frac{1}{T \bullet\ EPY}\right) \tag{10}$$

By substituting Equation (10) into Equation (8), the following equation can be given:

$$V(T) = -\frac{1}{a}\ln\left[\ln\left(\frac{T \bullet\ EPY}{T \bullet\ EPY - 1}\right)\right] + b \tag{11}$$

To apply Equation (11) to this work, Gumbel parameters *a* and *b* were calculated from the DMWS data set using Equations (6) and (7). In addition, 364.2 events/year was substituted to *EPY* of Equation (11) because the number of DMWSs for 10 years is 3,642. Finally, the EWS at a return period was estimated and the results are shown in Table 11 and Figure 13.

Table 11 Estimated extreme wind speed at a return period (Height: 80m).

Return period [year(s)]	*Prob(EWS,T)*	*ln(-ln(prob))*	EWS at 60m height [m/s]
1	0.99725	-5.90	30.4
5	0.99945	-7.51	35.7
10	0.99973	-8.20	38.0
25	0.99989	-9.12	41.0
50	0.99995	-9.81	43.3
100	0.99997	-10.50	45.6

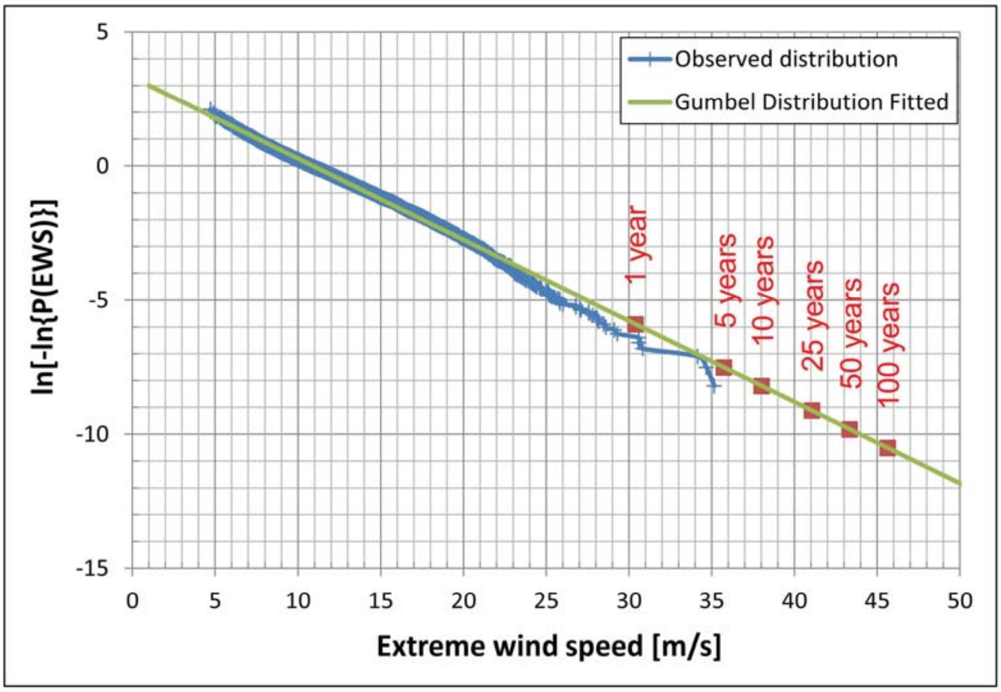


Fig. 13. Estimation of extreme wind speeds with Gumbel distribution fitted (Height: 80m).

The estimated EWS with a return period of 50 years is 43.3m/s. This value should be compared with the reference wind speeds which were provided by the IEC standard for the classification of the wind turbine. Then, the appropriate wind turbine class for the site is determined.

In addition, when taking into account the variation of the DMWS which was presented in Figure 11, the EWS occurred in the direction of northwest and in the time of 13:00 to 15:00. It may be an important indicator in both preventing accidents caused by strong wind as well as to predicting the EWS.

3.3 Analysis of turbulence intensity

Turbulence intensity (TI) is an important factor in the classification of the wind turbine. It is defined as the ratio of standard deviation to the average wind speed and commonly applied to the horizontal wind speed for the analysis of the site condition [29, 30, 31].

Turbulence intensity is computed by the following equation [2, 3]:

$$TI = \frac{\sigma}{V_{avg}} \tag{12}$$

where σ is the standard deviation of wind speed and V_{avg} is the average wind speed. In addition, standard deviation and average data are based on the 10-min recording interval [1].

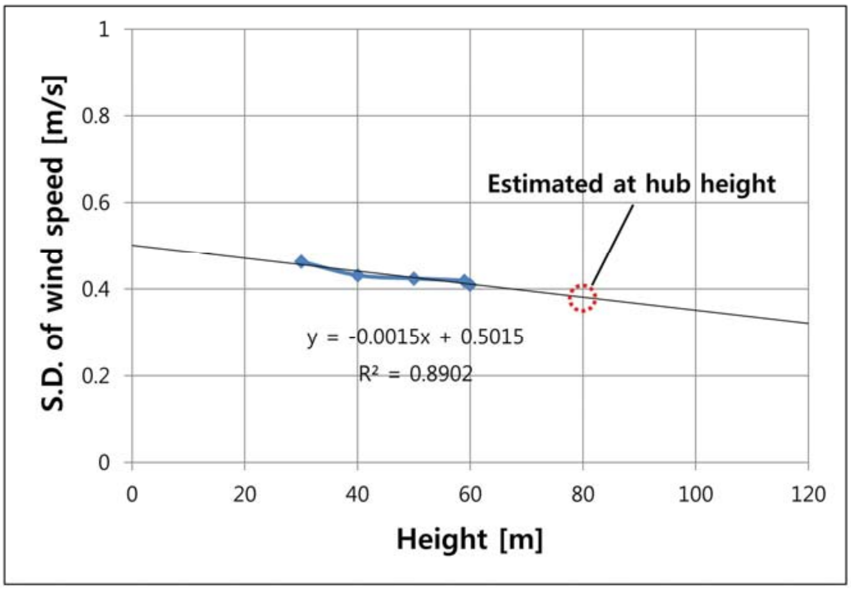
The turbulence intensity at hub height should be calculated to determine the wind turbine class but there is a problem in that the met mast heights measured are generally lower than hub height. Actually, hub height was assumed to be 80m while most wind data measured at Pyeongdae was done at 60m height, lower than hub height. To solve this problem, the following solutions were suggested; first, the hub height wind speed could be estimated using the wind shear exponent already mentioned above. Second, the hub height SD of WS could be obtained using the proposed estimation method which is based on correlation analysis.

3.3.1 A new method for the standard deviation estimation of wind speed

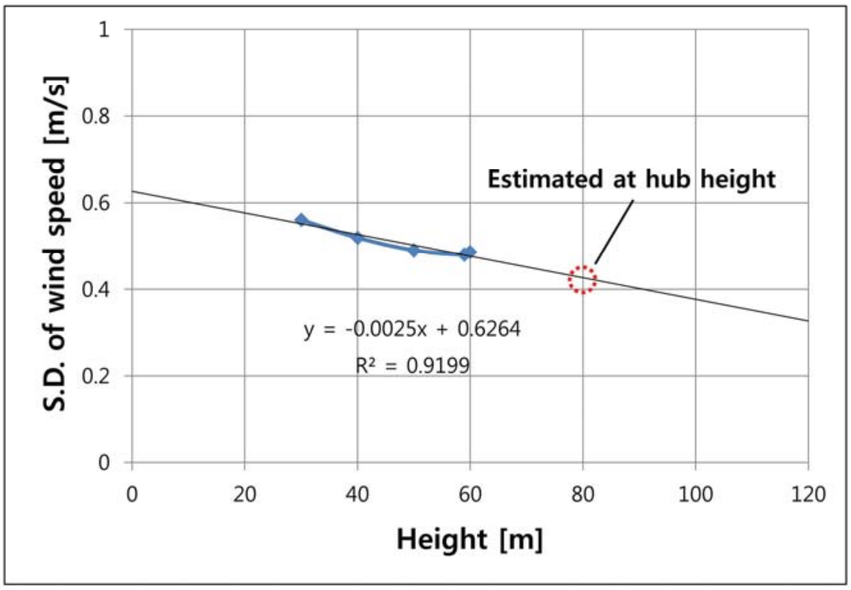
To estimate the SD of WS at a height higher than that measured, a new method was proposed in this study. This method is based on correlation analysis of the SD of WS with given heights. Correlation analysis was performed at each directional sector and also performed at each wind speed bin to increase estimation accuracy. In addition, the wind data, which showed numbers less than ten at each wind speed bin, were not used for correlation analysis to obtain more reliable results.

Actually, the SD of WS showed a higher correlation with the measurement height. Also they showed the linear relationship. Figure 14 shows the variation of the SD of WS with the height at the directional sector of N (345-15°). This sector was selected as the representative for all directional sectors. Figure 14(a) shows the variation at the wind speed bin of 3.5-4.5m/s while Figure 14(b) shows the variation at the wind speed bin of 4.5-5.5m/s. The higher correlation, confirmed from the determination of coefficient, R^2, was shown in the figures.

The complete results of this sector, N, can be checked in Table 12. Also, the number of data at each bin is presented in Table 13.



(a) Wind speed bin: 3.5-4.5m/s



(b) Wind speed bin: 4.5-5.5m/s

Fig. 14. Variation of the SD of WS with the height (Sector: N).

Table 12 The statistics of correlation analysis (Sector: N).

Wind speed bin [m/s]		Standard deviation of wind speed					A fitting result		
Start	End	H:60m	H:59m	H:50m	H:40m	H:30m	Slope	Intercept	R^2
0	0.5	0.05	0.04	0.04	0.08	0.04	-2.30E-04	6.05E-02	0.03
0.5	1.5	0.43	0.43	0.41	0.38	0.43	4.62E-04	3.95E-01	0.07
1.5	2.5	0.40	0.41	0.41	0.43	0.42	-7.05E-04	4.45E-01	0.64
2.5	3.5	0.39	0.39	0.40	0.40	0.42	-8.29E-04	4.39E-01	0.94
3.5	4.5	0.41	0.42	0.42	0.43	0.46	-1.50E-03	5.01E-01	0.89
4.5	5.5	0.49	0.48	0.49	0.52	0.56	-2.49E-03	6.26E-01	0.92
5.5	6.5	0.57	0.57	0.59	0.55	0.58	8.62E-05	5.70E-01	0.01
6.5	7.5	0.68	0.68	0.70	0.70	0.71	-8.08E-04	7.32E-01	0.70
7.5	8.5	0.74	0.75	0.77	0.72	0.75	1.53E-04	7.40E-01	0.01
8.5	9.5	0.81	0.82	0.85	0.79	0.82	3.77E-04	7.98E-01	0.05
9.5	10.5	0.92	0.92	0.94	0.88	0.91	9.48E-04	8.70E-01	0.34
10.5	11.5	1.00	1.01	1.02	0.92	0.94	2.62E-03	8.52E-01	0.63
11.5	12.5	1.09	1.10	1.13	1.14	1.14	-1.50E-03	1.19	0.82

Table 13 The number of data at each wind speed bin (Sector: N).

Wind speed bin [m/s]		Number of data				
Start	End	H:60m	H:59m	H:50m	H:40m	H:30m
0	0.5	83	93	89	36	59
0.5	1.5	151	156	162	147	142
1.5	2.5	217	216	213	165	146
2.5	3.5	428	404	403	218	235
3.5	4.5	414	416	418	289	292
4.5	5.5	327	329	317	228	220
5.5	6.5	245	239	258	163	161
6.5	7.5	283	292	287	148	137
7.5	8.5	303	301	295	153	158
8.5	9.5	252	247	255	115	119
9.5	10.5	300	309	311	65	60
10.5	11.5	244	247	250	38	38
11.5	12.5	236	233	235	25	23

The SD of WS at hub height was estimated using a linear extrapolation method. In addition, a linear extrapolation method was performed at each wind speed bin as well as at each directional sector. It is also confirmed in Figure 14. But there is a limit. The wind speed at hub height generally shows higher than the existing measurements because hub height is higher than the measurement heights of the met mast. If estimated wind speed at hub height shows higher than the measured wind speed, the SD of WS at hub height cannot be estimated using the above extrapolation method.

To solve this problem, another correlation analysis between estimated SD of WS and the wind speed was performed in this study. In addition, division of wind direction was also taken into account for this correlation analysis. Figure 15 shows the variation of the SD of WS with the wind speed at the directional sector of N (345-15°). Since it showed a higher correlation for a linear relationship, the SD of WS at hub height can be also estimated using a linear extrapolation method. Finally, the estimated values were extracted at each wind speed bin as well as at each directional sector. Then, the matrix for the SD of WS at hub height was made which matrix was given in Appendix A. This matrix is applied to the time-series wind data.

The process from correlation analysis to the application of the matrix has been commonly called a matrix method which is mainly used for MCP technique. A proposed estimation method also follows a similar process with the existing matrix method, but there is a big difference between them. The matrix method is usually used to predict the wind speed, while the proposed method in this study was used to predict the SD of WS.

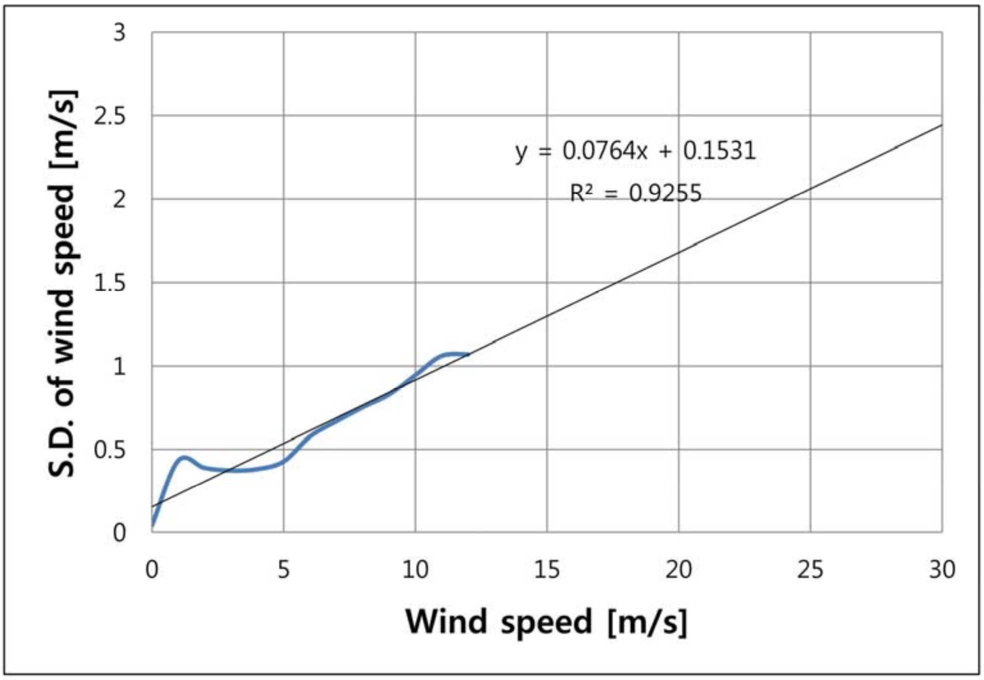


Fig. 15. Extrapolation with SD of WS to the higher wind speeds at 80m height (Sector: N).

3.3.2 The accuracy evaluation of a new method

In order to verify the performance of new method, the accuracy evaluation of the method was done by calculating the error rate. The process is as follows: The met mast wind data at the Pyeongdae site were measured at 60, 59, 50, 40 and 30m heights. To evaluate the accuracy, first, the SD of WS at 60m height was predicted by applying a new estimation method to the existing wind data at 50, 40 and 30m heights. Second, the estimated values of the SD of WS at 60m height were compared with the observed values at the same height and then, the error rates were calculated. The results are shown in Table 14.

Table 14 shows the observed and estimated values of the SD of WS at 60m height and also shows the relative error rates at each wind speed bin. The wind speed range for analysis is more than the cut-in speed of the wind turbines (generally, 4m/s) because the turbulence intensity is more important in the operating wind speed range than in the other ranges. In addition, differences between the observed and estimated values divided by the wind speed are presented in the table. It is useful to confirm the difference of the turbulence intensity between two values.

Table 14 The accuracy evaluation of a new method.

Wind speed [m/s]		Number of data	SD of WS at 60m [m/s]		Difference (Est-Obs)/V	Relative error [%]
Range	Median		Observed	Estimated		
3.5-4.5	4	5,148	0.452	0.457	0.0011	1.0
4.5-5.5	5	5,415	0.523	0.516	-0.0013	1.2
5.5-6.5	6	5,253	0.618	0.604	-0.0024	2.3
6.5-7.5	7	4,932	0.739	0.730	-0.0012	1.2
7.5-8.5	8	4,323	0.860	0.857	-0.0004	0.4
8.5-9.5	9	3,665	0.969	0.978	0.0011	1.0
9.5-10.5	10	3,146	1.081	1.085	0.0005	0.4
10.5-11.5	11	2,581	1.170	1.147	-0.0021	2.0
11.5-12.5	12	2,219	1.262	1.261	-0.0001	0.1
12.5-13.5	13	1,777	1.352	1.341	-0.0009	0.8
13.5-14.5	14	1,389	1.451	1.468	0.0012	1.1
14.5-15.5	15	959	1.575	1.584	0.0006	0.6
15.5-16.5	16	746	1.722	1.693	-0.0018	1.7
16.5-17.5	17	522	1.803	1.819	0.0009	0.9
17.5-18.5	18	403	1.924	1.944	0.0011	1.0
18.5-19.5	19	272	2.028	2.048	0.0011	1.0
19.5-20.5	20	142	2.043	1.976	-0.0033	3.3
20.5-21.5	21	48	2.133	1.858	-0.0131	12.9
21.5-22.5	22	12	1.875	2.204	0.0149	17.5
22.5-23.5	23	3	2.133	2.298	0.0072	7.7

The relative error rates were low at all wind speed ranges. It is confirmed that a new estimation method can effectively estimate the SD of WS at a higher height than the met mast. On the other hand, a new estimation method did not affect the determination of the wind turbine class because the difference of the turbulence intensity at 15m/s is

0.0006 which is a very low figure in comparison with the difference between each reference turbulence intensity for the classes, 0.02. The amount of data is an important factor affecting the accuracy of the method. In fact, as the amount of data decreased, the error rates tended to increase as shown in Figure 16. Therefore, a sufficient amount of data is required to apply this method.

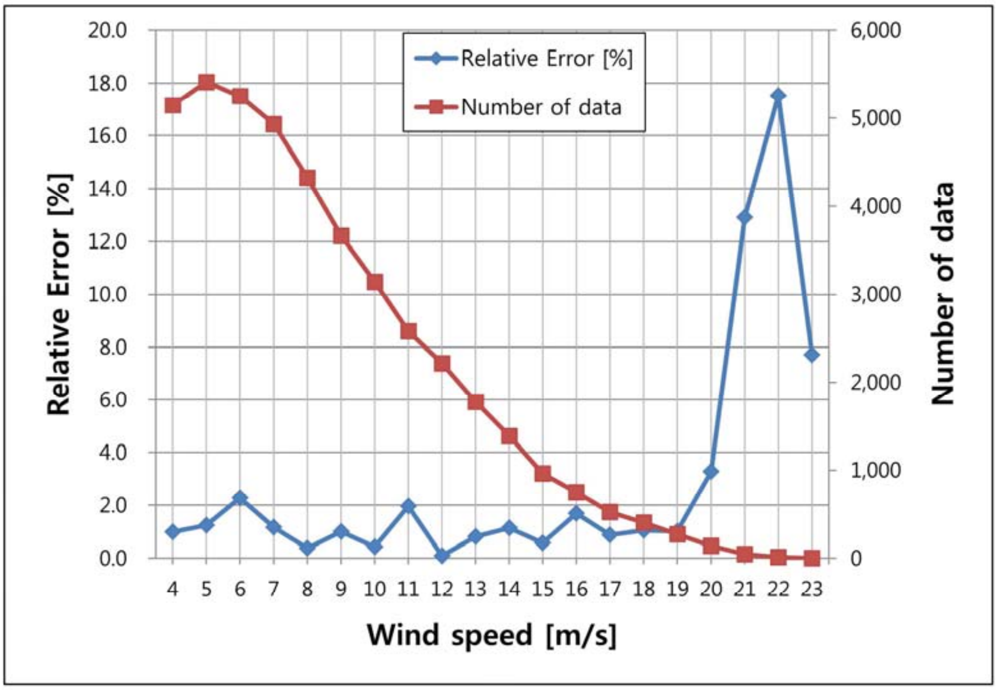


Fig. 16. Error tendency according to the number of data.

3.3.3 Estimation of turbulence intensity at the hub height

The average and standard deviation of wind speed at hub height can be estimated by using the wind shear exponent presented in Table 10 and the matrix for the SD of WS given in Appendix A. At this step, those estimated values should be applied to the existing time-series wind data. The example is shown in Table 15.

Table 15 An example of estimated time-series wind data.

Date & Time	Estimated wind speed (H:80m)	Estimated SD of WS (H:80m)	Wind speed (H:60m)	SD of WS (H:60m)	Direction (H:60m)
2010-02-07 0:00	7.8	0.62	7.4	0.79	108
2010-02-07 0:10	7.4	0.63	7.0	0.79	110
2010-02-07 0:20	7.1	0.63	6.7	0.70	118
2010-02-07 0:30	6.8	0.63	6.4	0.79	123
2010-02-07 0:40	6.6	0.63	6.2	0.67	122
2010-02-07 0:50	6.4	0.50	6.0	0.56	126
2010-02-07 1:00	6.6	0.63	6.2	0.54	125
2010-02-07 1:10	6.6	0.63	6.2	0.56	128
2010-02-07 1:20	6.4	0.50	6.0	0.59	125
2010-02-07 1:30	7.0	0.63	6.6	0.64	128
…	…	…	…	…	…

Turbulence intensity at hub height was calculated from the newly-formed time-series data by considering the division of wind direction. Here, wind direction data at 60m height were used for the division. On the other hand, in the IEC standard, the SD of WS is recommended to be used as the representative value which is given by the 90% quantile [1]. The quantile means the specific position which is taken to the given quantile value in the cumulative distribution function (CDF) of a random variable. Also, the representative value of the SD of WS can be calculated in the following equation:

$$\sigma_1 = \overline{\sigma} + 1.28\sigma_\sigma \qquad (13)$$

where σ_1 is the representative value which is 90% quantile and $\overline{\sigma}$ and σ_σ are the average and standard deviation values of the SD of WS, respectively. The estimated representative turbulence intensity at hub height is presented in Appendix B.

4. Determination of the wind turbine class

After calculating EWS and turbulence intensity at hub height, the appropriate wind turbine class was determined based on the IEC standard. Pyeongdae showed 43.3m/s of the EWS with a return period of 50 years. Since the estimated value of the EWS is between the reference wind speed of class I, 50m/s, and that of class Ⅱ, 42.5m/s, the appropriate wind turbine class is class I as presented in Table 16 [1]. On the other hand, in the table, the SD means the standard deviation of the EWSs. The EWS-added SD represents the maximum instantaneous EWS covering the fluctuation of the wind speed.

Table 16 Appropriate wind turbine class for extreme wind speed.

WTG's class	I	Ⅱ	Ⅲ
V_{ref} [m/s]	50	42.5	37.5
Estimated EWS [m/s]	43.3		
EWS+ 1×SD	47.8		
EWS+ 2×SD	52.3		
Proposed WTG's class	I		

Pyeongdae showed 0.10 of the average turbulence intensity at 15m/s. Since the estimated turbulence intensity is less than the reference value of class C, 0.12, the appropriate wind turbine class is class C as shown in Table 17 [1].

Table 17 Appropriate wind turbine class for turbulence intensity.

WTG's class	A	B	C
I_{ref}	0.16	0.14	0.12
Average TI at 15m/s	0.10		
Representative TI at 15m/s	0.13		
Proposed WTG's class	C		

Figure 17 shows the representative turbulence intensity according to wind speed at all directions, while Figure 18 presents the representative turbulence intensity at a sector of WNW (285-315°). The sector of WNW showed higher turbulence intensity than the other sectors.

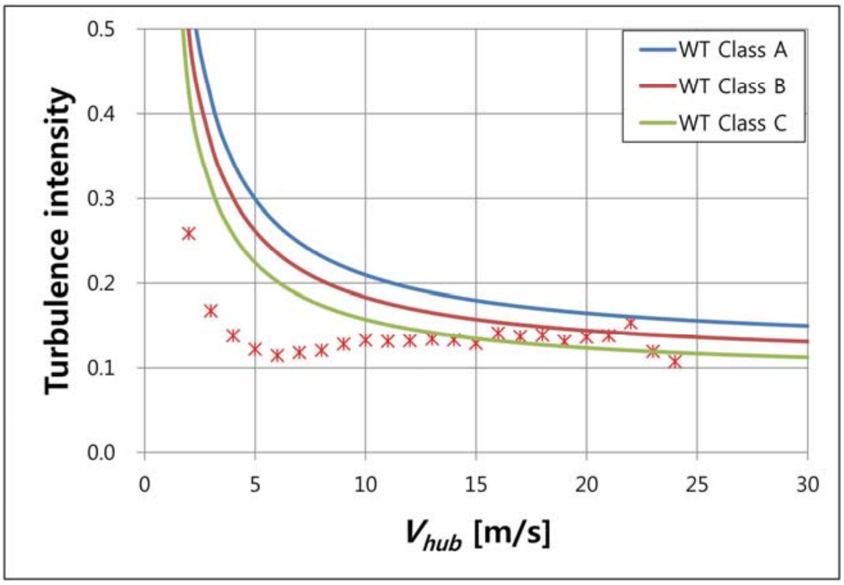


Fig. 17. Representative turbulence intensity at 80m height (All sectors).

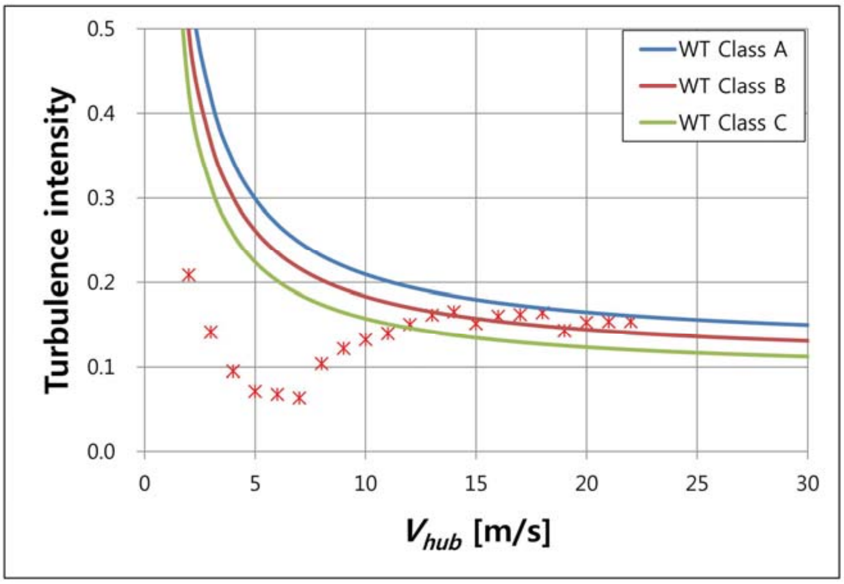


Fig. 18. Representative turbulence intensity at 80m height (Sector: WNW).

In the end, the appropriate wind turbine class for the Pyeongdae site is I C, as shown in Table 18.

Table 18 Appropriate wind turbine class at Pyeongdae.

Site	Proposed WTG's class
Pyeongdae	I C

5. Conclusions

In case that hub height of the wind turbine is higher than the measurement height, an ideal process to determine the wind turbine class was suggested in this study. Furthermore, an important assumption was made that only one wind turbine was installed at a potential wind farm site, so the wake effect was not considered. Also, the correction factor was not considered because the Pyeongdae site is not complex terrain; the roughness length at the site is 0.0214m, a value corresponding with the open terrain with a smooth surface.

Long-term wind data for 10 years were generated using the MCP technique. In addition, a new method was proposed to estimate the turbulence intensity.

1. For estimating extreme wind speed, the Gumbel distribution was used for an extreme distribution model and the daily maximum wind speed was used for the extreme data. Since Pyeongdae showed 43.3m/s EWS with a return period of 50 years, class Ⅰ was determined to be suitable for the site.

2. For estimating the turbulence intensity, a new method to predict the standard deviation of wind speed at hub height was proposed and the process is as follows: First, correlation analysis of SD of WS with the measurement height was performed at each directional sector and at each wind speed bin, respectively. Second, the matrix for the SD of WS at hub height was made and applied to the time-series real wind data. Third, the average and standard deviation of wind speed at hub

height was estimated using the wind shear exponent and the matrix. In the end, the turbulence intensity at hub height is calculated using the estimated figures above. Since Pyeongdae showed 0.10 of the average turbulence intensity at 15m/s, class C was determined to be suitable for the site.

3. The reliability of the new method in estimating standard deviation of wind speed was checked through accuracy evaluation. Since the error rate of the average turbulence intensity at 15m/s showed less than 1%, the method is suitable for determining the appropriate wind turbine class for the site.

References

[1] IEC 61400-1 Wind turbines – part 1 : Design requirements, IEC, 2005.

[2] Manwell, J.F., McGowan, J.G., Rogers, A.L., Wind Energy Explained: Theory, Design and Application, WILEY, 2010, 32-62.

[3] Pramod Jain, Wind Energy Engineering, Mc GrawHill, 2011, 127-151.

[4] Sathyajith Mathew, Wind Energy: Fundamentals, Resource Analysis and Economics, Springer, 2006, 46-52.

[5] Michael C. Brower, Wind Resource Assessment, Wiley, 2012, 117-129.

[6] Measnet: Evaluation of site-specific wind conditions, Version 1, Measnet, 2009, 14-18.

[7] Lee, B.; Ahn, D.; Kim, H.; Ha, Y. An estimation of the extreme wind speed using the Korea wind map. Renewable Energy 2012, 42, 4-10.

[8] Oh, K.; Kim, J.; Lee, J.; Ryu, M.; Lee, J. An assessment of wind energy potential at the demonstration offshore wind farm in Korea. Energy 2012, 46, 555-563.

[9] Rohatgi, J.; Araújo, A.; Primo, A. Extreme wind speeds and their prediction for wind turbines. Wind Eng 2013, 37, 595-603.

[10] Kang, D.; Ko, K.; Huh, J. Determination of extreme wind values using the Gumbel distribution. Energy 2015, 86, 51-58.

[11] García-Rojo, R. Algorithm for the estimation of the long-term wind climate at a meteorological mast using a joint probabilistic approach. Wind Eng 2004, 28, 213-224.

[12] Sreevalsan, E.; Das, S.S.; Sasikumar, R.; Ramesh, M.P. Wind Farm Site Assessment using Measure-Correlate-Predict (MCP) Analysis.

Wind Eng 2007, 31, 111-116.
[13] Weekes, S.M.; Tomlin, A.S. Comparison between the bivariate Weibull probability approach and linear regression for assessment of the long-term wind energy resource using MCP. Renewable Energy 2014, 68, 529-539.
[14] Carta, J.A.; Velázquez, S. A new probabilistic method to estimate the long-term wind speed characteristics at a potential wind energy conversion site. Energy 2011, 36, 2671-2685.
[15] Dinler, A. A new low-correlation MCP (measure-correlate-predict) method for wind energy forecasting. Energy 2013, 63, 152-160.
[16] WindPRO 2.9 User Manual, Chapter 11. MCP: Measure-Correlate-Predict, http://help.emd.dk/knowledgebase.
[17] Andrade, C.F.d.; Maia Neto, H.F.; Costa Rocha, P.A.; Vieira da Silva, M.E. An efficiency comparison of numerical methods for determining Weibull parameters for wind energy applications: A new approach applied to the northeast region of Brazil. Energy Conversion and Management 2014, 86, 801-808.
[18] Garcia, A.; Torres, J.L.; Prieto, E.; de Francisco, A. Fitting wind speed distributions: a case study. Solar Energy 1998, 62, 139-144.
[19] Farrugia, R.N. The wind shear exponent in a Mediterranean island climate. Renewable Energy 2003, 28, 647-653.
[20] Fırtın, E.; Güler, Ö.; Akdağ, S.A. Investigation of wind shear coefficients and their effect on electrical energy generation. Appl. Energy 2011, 88, 4097-4105.
[21] Gualtieri, G.; Secci, S. Wind shear coefficients, roughness length and energy yield over coastal locations in Southern Italy. Renewable Energy 2011, 36, 1081-1094.
[22] Ritter, M.; Shen, Z.; López Cabrera, B.; Odening, M.; Deckert, L. Designing an index for assessing wind energy potential. Renewable

Energy 2015, 83, 416-424.

[23] Rehman, S.; Al-Hadhrami, L.M.; Alam, M.M.; Meyer, J.P. Empirical correlation between hub height and local wind shear exponent for different sizes of wind turbines. Sustainable Energy Technologies and Assessments 2013, 4, 45-51.

[24] Gualtieri, G.; Secci, S. Methods to extrapolate wind resource to the turbine hub height based on power law: A 1-h wind speed vs. Weibull distribution extrapolation comparison. Renewable Energy 2012, 43, 183-200.

[25] Rehman, S.; Al-Abbadi, N.M. Wind shear coefficient, turbulence intensity and wind power potential assessment for Dhulom, Saudi Arabia. Renewable Energy 2008, 33, 2653-2660.

[26] Gumbel, E.J., Statistics of extremes, Columbia Univ Press, 1958.

[27] Ercelebl, S.G.; Toros, H. Extreme value analysis of Istanbul air pollution data. Clean - Soil, Air, Water 2009, 37, 122-131.

[28] Kochanek, K.; Renard, B.; Arnaud, P.; Aubert, Y.; Lang, M.; Cipriani, T.; Sauquet, E. A data-based comparison of flood frequency analysis methods used in France. Natural Hazards and Earth System Sciences 2014, 14, 295-308.

[29] Rehman, S.; Al-Abbadi, N.M. Wind shear coefficients and their effect on energy production. Energy Conversion and Management 2005, 46, 2578-2591.

[30] Türk, M.; Emeis, S. The dependence of offshore turbulence intensity on wind speed. J. Wind Eng. Ind. Aerodyn. 2010, 98, 466-471.

[31] Hui, M.C.H.; Larsen, A.; Xiang, H.F. Wind turbulence characteristics study at the Stonecutters Bridge site: Part I—Mean wind and turbulence intensities. J. Wind Eng. Ind. Aerodyn. 2009, 97, 22-36.

Appendices

Appendix A: The matrix for the standard deviation of wind speed at 80m hub height.

Appendix B: The representative turbulence intensity at 80m hub height (90% quantile).

Appendix A The matrix for the standard deviation of wind speed at 80m hub height.

Wind speed bin [m/s]			Standard deviation of wind speed [m/s]												
Median	Start	End	Avg.	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
0	0	0.5	0.06	0.04	0.07	0.07	0.07	0.04	0.08	0.07	0.07	0.08	0.05	0.06	0.07
1	0.5	1.5	0.40	0.43	0.40	0.37	0.41	0.38	0.37	0.43	0.44	0.48	0.40	0.37	0.36
2	1.5	2.5	0.40	0.39	0.44	0.36	0.39	0.40	0.41	0.38	0.55	0.56	0.47	0.36	0.31
3	2.5	3.5	0.41	0.37	0.40	0.34	0.42	0.39	0.38	0.39	0.54	0.67	0.45	0.38	0.42
4	3.5	4.5	0.43	0.38	0.46	0.36	0.40	0.43	0.40	0.39	0.47	0.86	0.43	0.35	0.48
5	4.5	5.5	0.48	0.43	0.52	0.39	0.42	0.45	0.43	0.44	0.52	0.94	0.47	0.33	0.57
6	5.5	6.5	0.54	0.58	0.54	0.40	0.50	0.50	0.63	0.58	0.69	0.85	0.47	0.39	0.62
7	6.5	7.5	0.63	0.67	0.64	0.46	0.52	0.63	0.77	0.80	0.82	0.73	0.40	0.42	0.76
8	7.5	8.5	0.78	0.75	0.67	0.57	0.53	0.62	0.90	0.92	0.94	1.06	0.71	0.79	0.88
9	8.5	9.5	0.89	0.83	0.75	0.63	0.49	0.64	1.00	1.08	1.07	1.16	0.89	1.05	0.99
10	9.5	10.5	1.02	0.95	0.81	0.64	0.72	0.83	1.20	1.31	1.21	1.25	1.60	1.28	1.08
11	10.5	11.5	1.10	1.06	0.75	0.69	0.79	0.89	1.38	1.35	1.37	1.34	1.60	1.49	1.17
12	11.5	12.5	1.20	1.07	0.86	0.78	0.86	0.97	1.35	1.57	1.36	1.43	1.89	1.74	1.28
13	12.5	13.5	1.29	1.15	0.96	0.78	0.97	1.00	1.70	1.78	1.52	1.53	1.65	2.04	1.38
14	13.5	14.5	1.39	1.22	0.99	0.82	1.10	1.12	1.69	1.82	1.58	1.62	1.78	2.25	1.49
15	14.5	15.5	1.49	1.30	1.04	0.86	1.02	1.13	1.92	1.84	1.68	1.71	1.91	2.22	1.61
16	15.5	16.5	1.67	1.38	1.10	1.04	1.07	1.19	1.88	2.27	1.78	1.80	2.04	2.51	1.78
17	16.5	17.5	1.74	1.45	1.15	0.99	1.13	1.26	2.29	2.18	1.88	1.90	2.17	2.71	1.78
18	17.5	18.5	1.93	1.53	1.21	1.04	1.19	1.32	2.19	2.31	1.98	1.99	2.30	2.89	1.90
19	18.5	19.5	2.12	1.60	1.26	1.08	1.24	1.38	2.31	2.43	2.08	2.08	2.42	2.67	2.12
20	19.5	20.5	2.18	1.68	1.31	1.13	1.30	1.45	2.44	2.56	2.18	2.17	2.55	3.00	2.21
21	20.5	21.5	2.28	1.76	1.37	1.18	1.35	1.51	2.56	2.69	2.28	2.27	2.68	3.16	2.29
22	21.5	22.5	2.28	1.83	1.42	1.23	1.41	1.58	2.68	2.82	2.38	2.36	2.81	3.32	2.35
23	22.5	23.5	2.38	1.91	1.47	1.27	1.46	1.64	2.80	2.95	2.48	2.45	2.94	3.48	2.45
24	23.5	24.5	2.48	1.99	1.53	1.32	1.52	1.70	2.92	3.07	2.58	2.54	3.07	3.65	2.56
25	24.5	25.5	2.58	2.06	1.58	1.37	1.58	1.77	3.04	3.20	2.68	2.64	3.20	3.81	2.66
26	25.5	26.5	2.68	2.14	1.63	1.42	1.63	1.83	3.16	3.33	2.78	2.73	3.32	3.97	2.76
27	26.5	27.5	2.78	2.22	1.69	1.46	1.69	1.89	3.28	3.46	2.88	2.82	3.45	4.13	2.86
28	27.5	28.5	2.89	2.29	1.74	1.51	1.74	1.96	3.40	3.59	2.98	2.91	3.58	4.29	2.97
29	28.5	29.5	2.99	2.37	1.79	1.56	1.80	2.02	3.52	3.71	3.08	3.01	3.71	4.45	3.07
30	29.5	30.5	3.09	2.44	1.85	1.60	1.86	2.09	3.65	3.84	3.18	3.10	3.84	4.61	3.17

Appendix B The representative turbulence intensity at 80m hub height (90% quantile).

Wind speed bin [m/s]			Turbulence intensity (90% quantile)												
Median	Start	End	Avg.	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
0	0	0.5	0.240	0.149	0.239	0.243	0.226	0.143	0.273	0.237	0.231	0.274	0.175	0.212	0.238
1	0.5	1.5	0.626	0.719	0.629	0.574	0.613	0.612	0.564	0.645	0.661	0.711	0.656	0.560	0.570
2	1.5	2.5	0.259	0.235	0.276	0.216	0.229	0.232	0.243	0.221	0.327	0.338	0.289	0.209	0.178
3	2.5	3.5	0.168	0.141	0.149	0.129	0.156	0.145	0.143	0.149	0.202	0.253	0.168	0.142	0.158
4	3.5	4.5	0.138	0.105	0.125	0.098	0.109	0.117	0.108	0.107	0.128	0.237	0.118	0.095	0.130
5	4.5	5.5	0.122	0.093	0.111	0.084	0.090	0.097	0.093	0.095	0.111	0.201	0.101	0.072	0.124
6	5.5	6.5	0.115	0.102	0.095	0.071	0.087	0.090	0.112	0.104	0.123	0.150	0.082	0.068	0.110
7	6.5	7.5	0.118	0.101	0.097	0.069	0.080	0.096	0.116	0.120	0.124	0.110	0.060	0.064	0.115
8	7.5	8.5	0.121	0.098	0.088	0.074	0.070	0.082	0.118	0.121	0.123	0.140	0.093	0.104	0.114
9	8.5	9.5	0.128	0.095	0.087	0.073	0.057	0.075	0.116	0.127	0.124	0.135	0.103	0.122	0.115
10	9.5	10.5	0.133	0.098	0.084	0.067	0.075	0.086	0.125	0.136	0.127	0.129	0.167	0.133	0.112
11	10.5	11.5	0.132	0.100	0.071	0.065	0.074	0.084	0.130	0.127	0.128	0.124	0.151	0.140	0.110
12	11.5	12.5	0.132	0.092	0.074	0.067	0.074	0.084	0.116	0.136	0.117	0.124	0.164	0.150	0.110
13	12.5	13.5	0.134	0.091	0.075	0.062	0.077	0.079	0.134	0.141	0.121	0.121	0.131	0.162	0.110
14	13.5	14.5	0.133	0.090	0.072	0.060	0.081	0.083	0.124	0.134	0.116	0.120	0.131	0.165	0.110
15	14.5	15.5	0.129	0.089	0.071	0.059	0.070	0.077	0.130	0.125	0.115	0.116	0.129	0.151	0.110
16	15.5	16.5	0.141	0.088		0.066	0.069	0.076	0.120	0.147	0.115	0.116	0.131	0.160	0.114
17	16.5	17.5	0.137	0.087		0.060	0.068	0.076	0.139	0.131	0.113	0.114	0.131	0.162	0.108
18	17.5	18.5	0.139	0.087		0.059	0.067	0.075	0.125	0.130	0.111	0.110	0.129	0.165	0.108
19	18.5	19.5	0.131	0.086		0.058	0.067	0.075	0.124	0.131	0.111	0.112		0.143	0.114
20	19.5	20.5	0.137	0.085			0.066		0.124	0.129	0.110	0.111		0.153	0.113
21	20.5	21.5	0.138	0.085			0.065		0.124	0.131	0.110			0.154	0.112
22	21.5	22.5	0.154	0.085					0.123	0.127				0.154	0.109
23	22.5	23.5	0.120	0.085					0.121						0.109
24	23.5	24.5	0.107												0.107

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2015. 6.

강 동 범 올림