Springer

Journal of Mechanical Science and Technology

Journal of Mechanical Science and Technology 23 (2009) 750~757

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-1206-y

Year-to-year variation in wind resource and assessment of WAsP prediction for wind machine power †

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(Manuscript Received February 13, 2008; Revised September 10, 2008; Accepted December 12, 2008)

Abstract

An investigation on inter-annual variations in wind resource and the accuracy of WAsP prediction was carried out in a real wind farm located at Hangwon, Jeju island, Korea. The wind data were obtained from an anemometer, and the wind vane installed on the meteorological mast and the operational data of the wind turbines tested were given by a monitoring system. The data were obtained for each six-month period in 2005 and 2006, respectively. As a result, it is clear that the wind characteristics vary year by year. Also, it was found that the cup anemometer on the meteorological mast in Hangwon wind farm was affected by the wake behind wind turbines. Considering the wake effect, the accuracy of WAsP prediction for the power production was assessed. The result shows that the relative error for the corrected power production that considered the wake loss was less than ±10 %.

Keywords: Availability; Wake loss; WAsP; Wind resource; Wind turbine power production

1. Introduction

The energy crisis and environmental problems have been treated as a global issue. They have led to the development of new and renewable energy all over the world. With regard to wind energy, as of the end of 2006, the total capacity of global wind power was almost 75,000 MW [1], and expected to increase to about 271,000 MW in 2015 [2]. As of the 2007, Korea has the cumulative installed capacity of 192 MW, and aims to achieve a total amount of 1,145 MW by 2012. However most of the wind turbines in Korea are foreign machines such as VESTAS from Denmark. The geared and direct types of 750 kW wind turbines were developed in Korea. In the near future, wind turbines from Korean manufacturers will be erected at strong wind sites in Korea.

Since inter-annual variations in wind characteristics occur, wind measurements for at least 5 years are required to obtain reliable wind data. However, due to the high price of instruments for acquisition of meteorological data, most researchers measure the wind conditions during short-term periods, for example, for one year or less. It is necessary to assess the wind resource in detail for more than one year in a candidate site to clarify variations in the energy output of a wind turbine as well as the wind conditions.

In order to estimate the wind resource and power production from a wind turbine at a site, the Wind Atlas Analysis and Application Program (WAsP) has been widely used in the world. The program includes BZ-

† This paper was recommended for publication in revised form by Associate Editor Won-Gu Joo
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model [3] for flow model, a roughness model and a sheltering obstacle model. In general, the prediction from WAsP agrees well with real data when the surrounding terrain is sufficiently gentle. Since Korea has a great deal of complex terrain, Kyong et al. [4] assessed the accuracy of WAsP prediction in complex terrain and furthermore proposed a method to enhance the accuracy [5]. In a real wind farm, Byun et al. [6] estimated the wind machine power from the result of WAsP prediction. Although the WAsP was developed to estimate wind energy potential mainly over land, Jimenez et al. [7] applied WAsP to assess offshore wind resource.

This investigation was conducted at Hangwon in Jeju island where wind turbines were operated commercially for the first time in Korea. We analyzed how the wind resource varies year by year using directly the wind data from the cup anemometer on a meteorological mast. Also, availability of the wind turbine tested was obtained from the turbine stop data. Furthermore, by applying WAsP to the wind farm, the accuracy of WAsP prediction for the power production from the wind turbines was assessed year by year.

2. Layout of wind turbines in Hangwon wind farm and measurement conditions

The Hangwon wind farm, which is located in the northeast part of Jeju island, Korea, has 15 wind turbine generator systems and a meteorological mast. The total amount of wind power capacity is about 9.8 MW, and manufacturers of the wind turbines are VESTAS and NEG-Micon.

Fig. 1 shows the layout of wind turbines in Hangwon wind farm, and the number 1 and number 2 wind turbines were tested for this investigation, which were erected in 1998. The two wind turbines were monitored to obtain the data for electric power production and for any troubles in them. In the figure, there is a meteorological mast (M.M.) close to the coast, from which 10 minute averaged wind data were obtained. The stop data of the wind turbine were recorded in Vestas Remote Panel, which is the system monitoring software provided by VESTAS. The data were obtained for each six-month period from April 1 to September 30, 2005 and 2006, respectively.

The type of the wind turbine tested is V42 of VESTAS, and wind power capacity is 600 kW. More detailed information about the wind turbine tested is listed in Table 1.

Table 1. V42-600kW wind turbine.

Item	Spec.
Generator spec.	Asynchronous 3-phased Optislip(VRCC)
Power control	Pitch control
Electrical spec.	Power: 600kW Voltage: 480V Pole No.: 4 RPM: 1800
Cut in wind speed	4 m/s
Cut out wind speed	25 m/s
Rotor diameter	42 m
Tower height	45 m

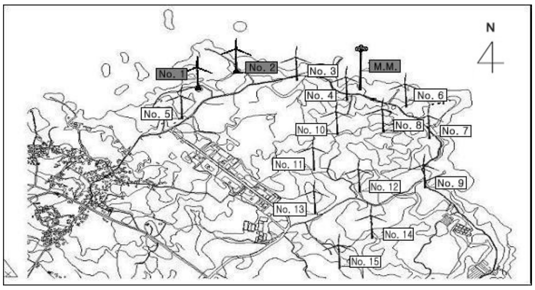


Fig. 1. Layout of wind turbines in Hangwon wind farm, Jeju island.

3. Wind data analysis and availability

The wind data were collected continuously at a sampling rate of 0.5 Hz. The sampled data were preprocessed in the data acquisition system, and the 10-minute averaged wind data sets were stored in it. The measurement period was the same as the system monitoring period.

Fig. 2 shows the average wind speeds for each month of the two years in the Hangwon wind farm. The wind speed data in 2006 were obtained from an anemometer on the meteorological mast installed at a height of 45 m above ground level, which corresponds to the hub height of the wind turbine tested. However, to obtain the wind speed data of 45 m height in 2005, the power law [8] was applied on the basis of the wind speed at a height of 37.5 m because of the malfunction of the anemometer at 45 m height in those days. For a feasibility study on application of the power law in this case, the wind speed data measured at 45m height in 2006 were compared with the result estimated from the power law on the basis of data measured at 37.5 m height in 2006. The comparison of actual wind speed data measured at 45 m height with the result of the extrapolation showed that the relative error was 1.8%. Accordingly, it was considered that the relative error due to the extrapolation of the wind speed at 45m height in 2005 would be similar to that of 2006.

In 2006, it is clear from Fig. 2 that the average wind speed had the lowest value in August and the highest value in September, ranging from 3.3 m/s to 7.3 m/s with six-month average of 5.5 m/s. In the case of 2005, the values are a little different from those of 2006. That is, the minimum and the maximum values in the average wind speed occurred in July and September, ranging from 4.5 m/s to 6.5 m/s with six-month average of 5.3 m/s. In both years, the maximum average wind speeds during the monitored period occurred in September because of typhoon NABI in 2005 and SHANSHAN in 2006 which passed near the Korean peninsula. Also, considerable variations in the monthly average wind speeds can be seen in 2006 compared with those in 2005.

The monthly average wind power densities of both years are shown in Fig. 3. The average wind power density, $\overline{P}/A$, is given by :

$$\overline{P}/A = \frac{1}{2}\rho\frac{1}{N}\sum_{i=1}^{N}V_i^3 \quad (1)$$

where, ρ = air density (assumed 1.225 kg/m^3 here), N = number of data, i = sample number, and V = wind speed averaged over 10 minutes.

Monthly variations in the average wind power density in 2006 were very high, while those in 2005 were low. In spite of similar values of the average wind speeds in April and September in 2006, the value of the average wind power density in April was much higher than that in September. That is because high wind speeds in April were more frequent than in September. Since the wind power density is proportional to the cube of the wind velocity, the higher wind speeds lead to much higher wind power density. The averages of monthly average wind power densities were 278.5 W/m^2 in 2006 and 223.8 W/m^2 in 2005, respectively.

The real wind speed distributions and Weibull distributions of both years are shown in Fig. 4. Using WAsP, the scale parameter, C, and the shape parameter, k , of Weibull probability density function could be obtained: 6.0 m/s and 1.66 for 2005, and 6.1 m/s and 1.51 for 2006, respectively.

The wind roses, which mean a diagram indicating the temporal distribution of wind direction, for both years

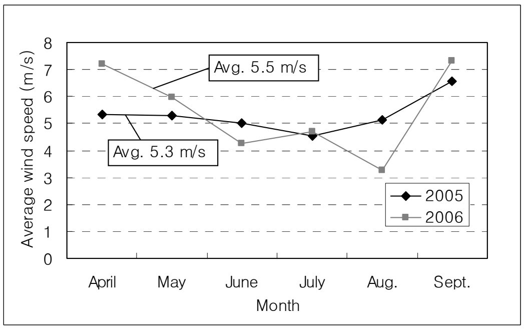


Fig. 2. The monthly average wind speeds.

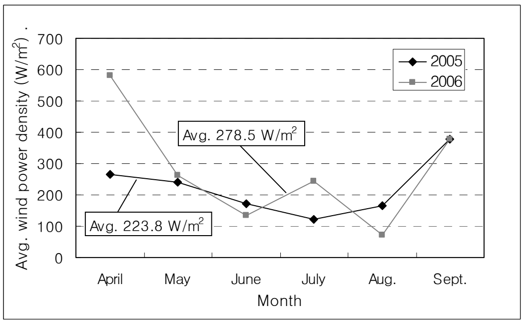


Fig. 3. The monthly average wind power densities.

are shown in Fig. 5. The prevailing wind directions in 2006 were from the west and the east-northeast, which accounts for 29 percent of total wind direction. For 2005, 78 percent of the total wind came from the north and the north-northeast. Variations in wind direction in 2005 were far smaller than those in 2006.

The turbulence intensities at 37.5m above ground level in 2005 and 2006 are shown in Figs. 6 and 7. The turbulence intensity, I , is defined by :

$$I = \frac{\sigma}{V} \quad (2)$$

where, V is the wind speed averaged over 10 minutes and σ is the standard deviation of it.

According to the IEC (International Electro-technical Commission) standard 61400-1 [9], both A category for higher turbulence characteristics and B category for lower turbulence characteristics are classified as the thick lines in the figures. Since the characteristic value of the turbulence intensity at 15 m/s provides the basis of classification of the wind turbine generator system, a vertical broken line is drawn at the wind speed of 15 m/s in the figures. In Fig. 6, all the data averaged over

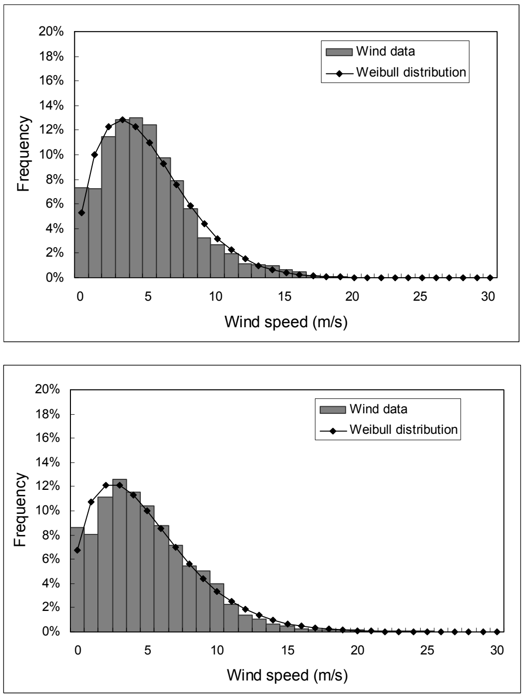


Fig. 4. The real wind speed distributions and Weibull distributions of 2005 (upper) and 2006 (lower)

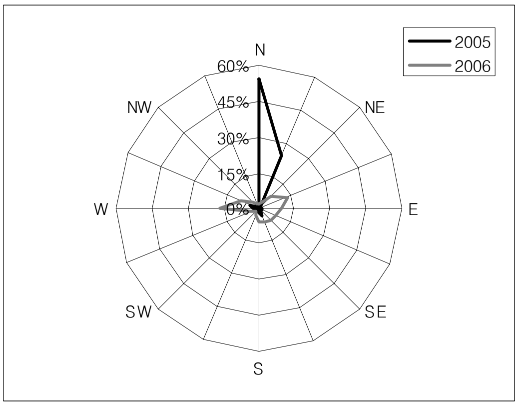


Fig. 5. Wind roses for both years.

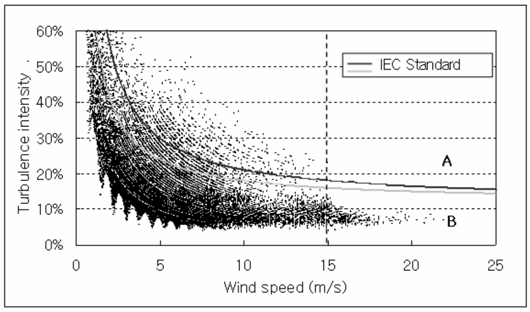


Fig. 6. The turbulence intensities at 37.5m above ground level in 2005.

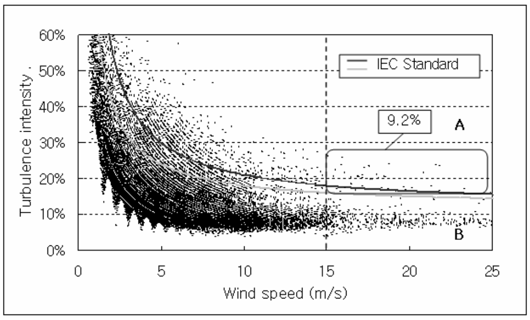


Fig. 7. The turbulence intensities at 37.5m above ground level in 2006.

10 minutes at the wind speed of 15 m/s belong to the B category. Consequently it was considered that there would be little machine trouble due to the higher turbulence intensity in 2005.

On the other hand, in 2006 of Fig. 7, some of the wind data over 15 m/s are distributed in the A category and transition zone. They account for 9.2 percent of all the wind data stronger than 15 m/s. Most of these higher turbulence characteristics came from typhoon EWINIAR, which went directly through Jeju island on July 10, 2006. A typhoon can affect the fatigue life of turbine components, electric devices, and the lifetime of the wind turbine, and furthermore become the cause of wind machine trouble.

Table 2 shows the availabilities as well as the number of stops and the time stopped of the number 1 wind turbine. The availability is calculated by the following formula [10]:

$$Availability = \frac{T_1}{T_2} \times 100\ (\%) \tag{3}$$

where, T_1 is total number of hours during a certain period excluding the number of hours for maintenance or fault situations, and T_2 means total number of hours during the period.

It can be seen in the table that the longest time stopped occurred in September for both years. The availability averaged over six months decreased from 92.6 percent in 2005 to 83.7 percent in 2006.

As for the number 2 wind turbine, the number of stops, the time stopped and the availabilities are shown in Table 3. The wind turbines stopped for the longest time in July 2005 and in August 2006, respectively. The

Table 2. The number of stops, the time stopped and the availabilities of the number 1 wind turbine.

Month	2005			2006		
	No.	time (h:m:s)	Avail. (%)	No.	time (h:m:s)	Avail. (%)
Apr.	30	24:37:12	96.6	50	142:06:11	80.3
May	33	20:14:36	97.3	44	104:54:55	85.9
Jun.	18	12:09:13	98.3	8	66:35:15	90.8
Jul.	12	2:13:00	99.7	21	131:53:34	82.3
Aug.	32	89:39:29	88.0	8	99:56:31	86.6
Sep.	43	175:57:14	78.8	11	170:37:18	76.3
Total or Avg.	168	324:47:44	92.6	139	716:03:44	83.7

Table 3. The number of stops, the time stopped and the availabilities for the number 2 wind turbine.

Month	2005			2006		
	No.	time (h:m:s)	Avail. (%)	No.	time (h:m:s)	Avail. (%)
Apr.	0	0:00:00	100	2	4:08:49	99.4
May	1	2:26:58	99.7	2	3:47:13	99.5
Jun.	0	0:00:00	100	3	1:04:47	99.8
Jul.	9	182:58:51	75.4	7	4:31:49	99.4
Aug.	3	70:11:37	90.6	13	199:22:03	73.2
Sep.	2	71:07:01	90.1	0	0:00:00	100
Total or Avg.	15	326:44:27	92.6	27	212:54:41	95.2

availability averaged over six months increased from 92.6 percent in 2005 to 95.2 percent in 2006.

4. WAsP prediction for wind turbine power production

To apply WAsP to this investigation, roughness lines, which represent the roughness of a terrain surrounding a site, were drawn in the digital map for the Hangwon wind farm by using the Map Editor. The result is shown in Fig. 8. There were no sheltering obstacles in the site which are defined as “obstacle” in WAsP. In the figure, the roughness lengths for the sea, a very small island, the place close to the coastal line, and farm land with many trees and bushes were designated as 0.00 m, 0.01 m, 0.1 m, and 0.2 m, according to the WAsP manual. The building for fish ponds and suburbs were also designated as 0.5 m.

According to the IEC international standard [10], the wind data from the meteorological mast are affected by the wakes of neighboring and operating

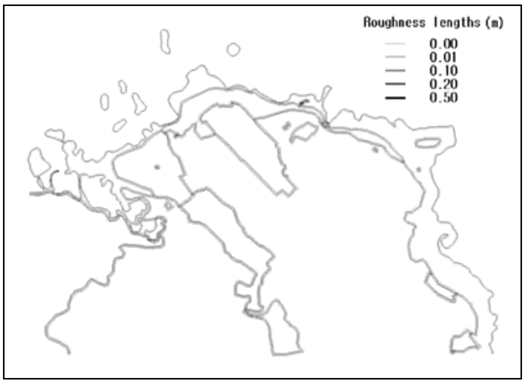
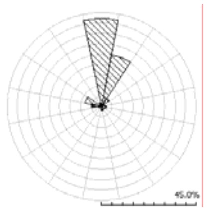


Fig. 8. Roughness map for the Hangwon wind farm.

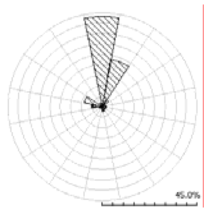
wind turbines. In this work, the wind speed at the meteorological mast seemed to decay because of neighboring and operating wind turbines, as shown in Fig. 1. Thus we tried to estimate the wakes behind neighboring wind turbines using WAsP. That is, a dummy wind turbine was installed at the point of the meteorological mast in the digital map, which was the same type as the wind turbine tested. Next, for the purpose of more accurate analysis, we excluded the wind data when the turbines were stopped for machine trouble. Then, all the rest of wind data were inputted into the WAsP, and finally the annual energy production, AEP, and the wake loss of the dummy wind turbine were outputted by running WAsP.

Each directional AEP and wake loss of the dummy wind turbine is shown in Fig. 9. Each of the total wake losses is indicated in each small title of the figure. In 2005, since the wind mainly blew from the north, which did not have any obstacles, not much wake loss occurred , only about 4 percent. On the other hand, in the 2006, the wake loss was about 10 percent. The WAsP predicted mainly the wake from the west wind because the number 1, 2 and 3 wind turbines were located in the west of the dummy wind turbine. Although there were several wind turbines to the south of the dummy wind turbine, the wake loss due to the south wind was low. That is because the prevailing wind direction was not from the south. This result means that the cup anemometer on the meteorological mast in the Hangwon wind farm is affected by the wake behind neighboring wind turbines.

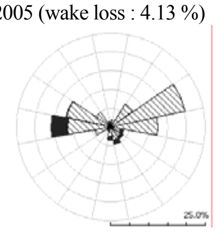
The wake loss obtained from the dummy wind turbine was applied to the prediction of the power production of the real wind turbine. The following formula was defined in this work to obtain the corrected power production, $\tilde{P}$, which takes into account the



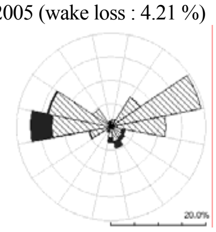
(a) The result from wind data of No.1 wind turbine in 2005 (wake loss : 4.13 %)



(b) The result from wind data of No.2 wind turbine in 2005 (wake loss : 4.21 %)



(c) The result from wind data of No.1 wind turbine in 2006 (wake loss : 10.26 %)



(d) The result from wind data of No.2 wind turbine in 2006 (wake loss : 10.34 %)

Fig. 9. Directional AEP and wake loss of the dummy wind turbine.

wake loss behind wind turbines.

$$\tilde{P} = P_{WAsP} + (wake\ loss \times P_{WAsP}) \qquad (4)$$

where, P_{WAsP} is the power production predicted by WAsP that does not take the wake loss into account.

Also, the WAsP calculates the mean power production, $\overline{P}$, based on the following equation:.

$$\overline{P} = \int_0^\infty P_w(V)\, p(V)\, dV \qquad (5)$$

where, $P_w(V)$ is a known machine power curve and $p(V)$ is the Weibull probability density function. When wind turbine power production was estimated in this work, the data by typhoon with wind speed more than 25 m/s were excluded in accordance with equation (5).

Power productions were estimated by using WAsP and Eq. (4). Fig. 10 shows the comparison of the original power production predicted by WAsP with the corrected power production considering the wake loss for the number 2 wind turbine in 2006. The real power production is also represented in the figure. The corrected power production is in better agreement with the real power production compared with the original power production by WAsP. Therefore, when the wind data obtained from the cup anemometer on a meteorological mast in a real wind farm are used for WAsP, the

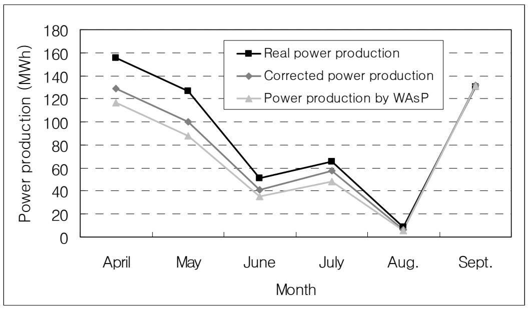


Fig. 10. Comparison of the three types of power production for the number 2 wind turbine in 2006.

wake loss behind neighboring wind turbines should be considered, and the original power production by WAsP should be corrected taking into account the wake loss.

For August, the difference between the power production by WAsP, the corrected power production and the real power production looks very small. However, the relative error for the corrected power production was about 20 %, and it also had similar values for April to July. The relative error is expressed by:

$$relative\ error = \frac{true\ value - predicted\ value}{true\ value} 100\% \qquad (6)$$

Unlike the other months, the three power productions had almost the same values in September, which means the power production predicted by WAsP agrees well with the real one. A wake loss of 0.5 % occurred in September, while wake losses of 10 % to 20 % occurred in April to August. It was considered that was why the difference between the three types of power productions was considerably smaller in September than in the other months.

Table 4 shows a comparison of the corrected power productions that considered the wake loss and the real power production from the wind turbines tested. The monitored period, the generator operating hours, the AEP by WAsP prediction and the mean power production derived from the AEP are also indicated in the table. Because the number 2 wind turbine had conducted a so-called “half operation” in September of 2005 due to a technical problem, the period was excluded. From Table 4, the relative error for the corrected power production was less than ±10 % in this investigation. The result would be helpful when one estimates the power production using WAsP at a candidate site for wind development.

Table 4. Comparison of the corrected power production and the real power production.

Items	No.1 W.T., 2005	No.2 W.T., 2005	No.1 W.T., 2006	No.2 W.T., 2006
Monitored period	Apr.-Sep. 2005	Apr.-Aug. 2005	Apr.-Sep. 2006	Apr.-Sep. 2006
Generator operating hours (hrs)	4067	3416	3676	4179
AEP by WAsP prediction (MW)	752.101	795.868	881.506	1019.986
Mean power production by WAsP (kW)	85.856	90.852	100.628	116.436
Corrected power production (MW)	349.177	310.352	369.910	486.589
Real power production (MW)	338.561	318.366	338.144	538.495
Relative error (%)	-3.14	2.52	-9.39	9.64

5. Conclusions

To clarify inter-annual variations in wind resource and assess the accuracy of WAsP prediction, an investigation was carried out in Hangwon wind farm in Jeju island, Korea, for each six-month period from April 1 to September 30, 2005 and 2006, respectively. The result of the wind data analysis shows that the wind characteristics such as the monthly average wind speed, the wind rose and the wind power density vary year by year. Also, to estimate the wake behind neighboring wind turbines, a dummy wind turbine was set at the point of the meteorological mast in the digital map. The result showed that the cup anemometer on the meteorological mast in the Hangwon wind farm was affected by the wake behind neighboring wind turbines. Considering the wake effect, the accuracy of WAsP prediction for power production was assessed. By comparing the real power production with the corrected power production that took into account the wake loss, it was found that the relative error for the corrected power production was less than ±10 % in this work.

Acknowledgments

This work was supported by Clean Energy Division, Jeju Special Self-Governing Province.

Nomenclature

$\overline{P}/A$	:	Average wind power density
V	:	Wind speed averaged over 10 minutes
I	:	Turbulence intensity
$\tilde{P}$	:	Corrected power production
P_{WAsP}	:	Power production predicted by WAsP
$\overline{P}$	:	Mean power production
P_w	:	Wind machine power curve
p	:	Weibull probability density function

Greek Symbols

ρ	:	Air density
σ	:	Standard deviation

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