

Article

Study on Atmospheric Stability and Wake Attenuation Constant of Large Offshore Wind Farm in Yellow Sea

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Abstract: Power generation estimation is one of the key steps in wind farm micro-sitting, and its accuracy is related to the wake decay constant in the wake model. Considering the influence of wind resource distribution in different regions, this study carried out interval optimization for the wake decay constant of offshore wind farms in the Yellow Sea region of China. Given the very small length of the sea surface roughness, atmospheric stability is a critical factor influencing the wake extent and recovery speed of offshore wind farms. WASP 10 (Wind Atlas Analysis and Application software) simulates the wake of various scenarios, and the selection range of wake attenuation constant is investigated by combining the cases of two offshore wind farms in the Yellow Sea region. The study found that the higher the atmospheric stability, the larger the wake and the lower the wake attenuation coefficient. The Yellow Sea wind farm's wake error system is between 0.03 and 0.04, and the forecast error can be controlled to within 3%. When simulating the wind farm at Yellow Sea offshore for improving power generation and economic evaluation, it is critical to select the correct value range of wake decay constant.



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Keywords: wind farm in coastal waters; evaluation of power generation; wake decay constant; WASP; wake flow

1. Introduction

With the rapid growth of energy demand and the rapid consumption of fossil fuels, wind energy, as a renewable energy, has attracted the attention and promotion of all countries in the world. According to the statistics, the global cumulative wind power capacity is 837 GW, compared with 2021 increased by 12%, the total installed capacity of wind power in China has exceeded 307 GW in 2021 and this number is continuously rising [1]. China commitment on the COP 21 conference in Paris that China to reduce CO₂ emissions 180 Mt by 2030 [2], that is complemented by China's increased offshore wind power capacity during the past decade. Both BNEF and 4C indicate strong global wind power growth with over fivefold increase in offshore wind power deployment projected over the next decade, and China offshore wind power will cumulatively deploy between 65 and 77 GW by 2031 [3].

With the large-scale development of onshore wind resources, promoting and developing offshore wind power has become a major development trend of the world wind power industry. Offshore wind power has the advantages of higher wind resource quality and less impact on residents' lives away from crowds, according to the study. The disadvantage is that the construction costs are higher [4]. However, compared with onshore wind energy,

offshore wind energy still has higher power generation costs. In order to improve the economy of offshore wind power projects, it is necessary to select appropriate difference assessment technology and application software for offshore wind resource distribution assessment [5].

Coastal waters rich in wind resources are becoming a focus of investment in the wind power industry. The wake effect is an important consideration in the planning and design of wind farms, particularly offshore wind farms. The wake will not only cause a decrease in downstream wind speed and a loss of power generation, but it will also cause an increase in fatigue load as turbulence intensity increases. Accurate assessment of wind farm wake effect is especially important for wind power projects. Many researchers have conducted a study on the calculation of power generation for the offshore wind farm by applying different simulation software of wind farm. According to the wind flow model, there are currently three categories of common wind farm simulation design software. The wind industry software standard WAsP (Wind Atlas Analysis and Application software) [6], which is a linear model, represents the first group. The second group, represented by WindSim [7] and WT [8], is the CFD model, which is frequently used in onshore wind power project. OpenWind [9] is the third group of mass conservation model. WAsP is a software researched, developed and promoted by Denmark Riso National Laboratory, and it widely used in the areas with relatively simple terrains [10,11]. WindSim is a wind farm design software based on CFD that is mainly used for the simulation and calculation of wind flow fields at complex terrains [12,13]. WT software defines the boundary layers and automatically produces the boundary conditions based on the surrounding scenes of flow fields, and using the computing strengths of CFD, conduct a more accurate simulation and calculation [14]. Wind flow field simulation software based on CFD models can simulate wind flow field more precisely in complex terrain [15,16], but WAsP has good accuracy in modeling wind flow field at offshore [17,18], and because the sea level can be thought of as an approximately flat terrain with a very tight roughness length, the WAsP linear wind flow model performs well in terms of accuracy and calculation speed when simulating offshore wind resources [19]. At the moment, CFD software requires more computer resources and time, so WAsP is an excellent option for offshore wind power engineering. It has been demonstrated that OpenWind's simulation accuracy primarily depends on the initial input data [20,21], and as this application is not as widely used as others, further investigation is required to prove mass conservation model can be used to simulate the wind flow field. In this research, we plan to use WAsP software in the hope of providing reference for more wind resources. Argin et al. (2017) use WAsP to do the statistical analysis of wind speed and wind direction data for 20 sites in the Black Sea coastal region [22].

Since complicated nonlinear phenomena that wake loss generated by wind farm are difficult to simulate with accuracy, it is hard to calculate how much wind farm wake loss will occur. NO. Jensen (Park) wake model is the most classic [23], and Katic et al. (1986) modified it for wind farms [24]. In offshore wind projects, the Park wake model is frequently used to calculate annual energy production (AEP). Numerous research has been conducted to validate the applicability of the PARK model, and it has always been one of the recommended models [25], and other wake models use it as a standard to evaluate the model [25,26]. Barthelmie R et al. conducted the research on the Nysted offshore wind farm and indicated that the value of wake decay constant should be various if calculating the power generation of wind farm by using WAsP. If compared with the actual power generation of Nysted offshore wind farm, it applied to value the wake decay constant stimulated and calculated as 0.03. However, the wake decay constant should be of a higher value in the Homs Rev 1 wind power project [27]. Through comparison, the wake decay constant in WAsP calculation should be lower than the value recommended in software if simulating the power generation plant [17]. A Peña et al. (2014) demonstrated that when WAsP is used to compute the power generation of offshore wind farms, the wake decay constant of the Park wake model is frequently lower than the recommended value of WAsP when the atmosphere is neutral [28]. They also noted it in the Horns Rev1 project research

that the simulation result was closest to the actual value when wake decay constant was typically set at 0.05 [29].

In one experiment, instruments were used to measure the evolution of wind turbine wakes and turbulence under neutral and unstable atmospheric conditions [30]. A study that analyzed the influence of atmospheric stability on wind turbine wakes using large eddy simulation found that when the atmosphere is stable, the recovery of wind turbine wakes is slow, and when the atmosphere is unstable, the recovery of wind turbine wakes is faster [31]. Atmospheric stability analysis is crucial during the wind resource assessment process.

According to previous study, when many offshore wind farms use WAsP to calculate power generation, the wake decay constant is lower than the recommended value, which means that the expected power generation is overestimated, and revenue may be much lower than expected when the wind farm is operational. As an example, this paper uses the WAsP wind farm design software selected by the two wind farms in the feasibility study, as well as the PARK wake model to calculate AEP, and inputs the terrain, roughness, and other parameters into WAsP to solve the entire wind farm wake. The range of attenuation wake attenuation constant suitable for the Yellow Sea coastal wind power engineering is analyzed by comparing the solution and the actual wake.

The basic principles of the WAsP and Park wake models, as well as the classification method of atmospheric stability, will be described in the second chapter of this paper. In the third chapter, the author uses two typical offshore wind farms as examples to examine in depth the effect of attenuation constant on the overall wake of the wind farm. Finally, the fourth chapter summarizes the paper's research findings.

2. Methods

2.1. Wind Atlas Analysis and Application Software (WAsP)

The Wind Atlas Analysis and Application software (WAsP) calculation core is the BZ model of Troen (1990) [32], which was improved in 1990 and is based on the linear calculation model proposed by Jackson and Hunt (1975) [6]. It has the following characteristics:

- (1) Calculate the wind flow wave around the polar coordinates of the model by combining with the terrain analysis program;
- (2) It integrates the surface roughness for application in case of multi-scale decomposition, and calculates the structure of internal layers through calculating the balance conditions among surface pressure, pressure gradient and advection;
- (3) The thickness of the atmospheric boundary layer it applies is 1 km, enabling the large-scaled wind flow to aggregate around the model.

The wind may have changes of microscale due to the influences of environment and landform, but it still has the characteristics of common mesoclimate. Based on this principle, it is able to calculate the mesoscale characteristics in surrounding areas upon measuring the wind at anemometer tower and removing the microscale change generated in case of applying WAsP model. When calculating the characteristics for other points in surrounding areas, it is able to calculate the microscale results for wind resources at other points though linear simulation upon considering the factors that influence microscale (e.g., roughness, etc.) [33].

2.2. The Park Wake Model

Park model has been improved in the engineering construction, and becoming the Park wake model applied by WAsP. Using momentum-deficit theory, this model predicts the flow field simply: the wake is assumed to expand linearly behind the rotor. As a result, the only variables are the initial velocity deficit at the start of the wake, calculated from the C_t -coefficient at actual wind speed, and the wake decay constant, which is the rate of wake expansion (break-down). It is assumed that the boundary line of wake flow tends to be expanded and the boundary width is set as $D + 2kx$, thus its main expression is shown as below [34].

Expression for the Park model:

$$V_{\text{DOWN}} = V^{\text{UP}} \left[1 - \left(1 - \sqrt{1 - C_r} \right) \left(\frac{D}{D + 2kx} \right)^2 \right] \quad (1)$$

The wake decay constant governs how quickly the wind field behind the wind turbine returns to freestream. Expression for attenuation wake decay constant:

$$k = \frac{1}{2(\ln(Z/Z_0))} \quad (2)$$

In which, V_{DOWN} is the wind speed downwind of the wind turbine, and its unit is m/s; V^{UP} is the wind speed upwind of the wind turbine, and its unit is m/s; C_r is the wind turbine's thrust coefficient; D is the wind turbine's impeller diameter, and its unit is m; k is the wake decay constant; x is the distance between wind generation set; Z is the wind turbine's hub height; Z_0 is the surface roughness.

2.3. Method to Analyze the Atmospheric Stability Class

Because atmospheric stability is an important factor influencing wind farm wake attenuation, the value of the wake decay constant must be adjusted to account for atmospheric stability. It related the value of the wake decay constant to the atmospheric stability class; if the atmosphere is stable, the wake decay constant must be reduced. Atmospheric stability has been shown in studies to have a significant impact on wind speed attenuation and turbulence intensity in the wake region. The recovery of wind speed after the wake is faster in the convective boundary layer than in the neutral and stable atmospheric situation [35].

Consider the temperature gradient method for determining the stability of atmosphere dynamics. It also categorizes atmospheric stability by representing vertical turbulence characteristics. This method is commonly used in flat areas and is appropriate for sea surfaces with single underlying surfaces. This article will make use of the formulas and classification tables (Table 1) listed below [36,37].

Table 1. Atmospheric stability class value table.

Stability Classes	$\Delta T/\Delta z$ ($^{\circ}\text{C}/100\text{ m}$)	Atmospheric Stability
A	<-1.9	Highly unstable or convective
B	$-1.9 \sim -1.7$	Moderately unstable
C	$-1.7 \sim -1.5$	Slightly unstable
D	$-1.5 \sim -0.5$	Neutral
E	$-0.5 \sim 0.5$	Moderately stable
F	$0.5 \sim 4.0$	Extremely stable

Atmospheric stability equation:

$$\frac{\Delta T}{\Delta z} = \frac{T}{\theta} \times \frac{\Delta \theta}{\Delta z} - \gamma_d$$

T : Temperature

z : Height

θ : Potential temperature

γ_d : Dry adiabatic lapse rate

3. Method Application and Result Analysis

In this paper, two large-scale offshore wind farms in Liaoning and Jiangsu, China, are selected as case studies. The Park wake model is used to estimate the power generation of the wind farm, and the wake flow loss error of power generation estimation under different wake decay constant is obtained.

WAsP recommends a default value for the wake decay constant of 0.075 in onshore wind farm, and 0.04–0.05 for offshore. In this study, WAsP will be used to calculate wake losses at different wake decay constant ranging from 0.03 to 0.75. Modeling parameters using as Table 2.

Table 2. WAsP software modeling parameter.

Category	Parameter	Value
Data parameter	Measured topographic map	SRTM
	Topographic map scale	1:2000
	Roughness length	0.0001
Model Parameter	Software model	IBZ model
	Sector step size	22.5
	Grid Node Spacing	100 m
	Wake Model	Park

3.1. Case Study in Xutuozi Wind Farm

3.1.1. Case Description

The planned capacity for Xutuozi wind farm is 300 MW, as shown in Figure 1. The wind farm is located in Liaoning Province, an offshore area in the Yellow Sea's northwestern. The project's center is 19 km from the coastline with an ocean area is 48 km². One wind anemometer tower is on the project, number 5#, annual wind date from 1 November 2017~31 October 2018. The annual average wind speed at 105 m height of 5# tower is 6.7 m/s during the assessment period, the main wind direction is North as shown in Figure 2, and the mean turbulence intensity at 15 m/s is 0.0582, which is lower than IEC category C. By analyzing wind farm SCADA data, this project's wake flow loss is approximately 13.34%, and its annual energy production is 715.87 GWh. Figure 1 depicts the wind farm layout; the turbine separation distance in the main wind direction is 13 rotor diameters and 3 diameters in the crosswind direction. Parameter settings for calculation using WAsP are shown in Table 2.

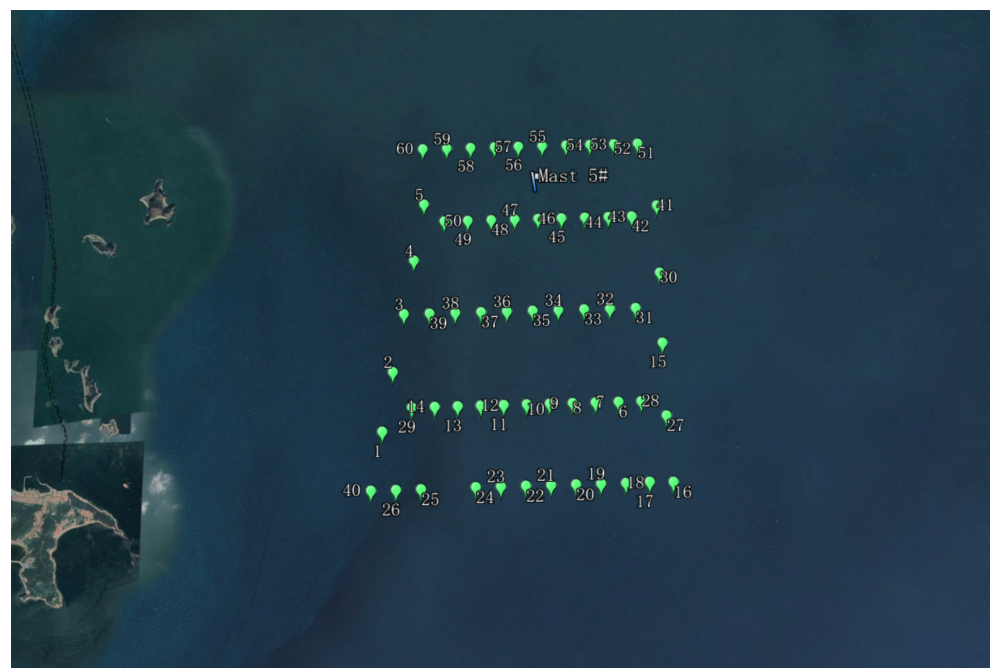


Figure 1. Schematic diagram for site layout of wind farm and position of met-mast.

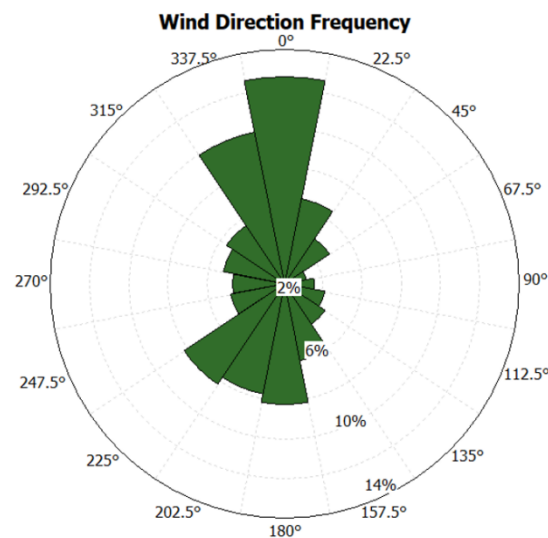


Figure 2. Wind direction rose of 5#.

3.1.2. Results and Discussions

Upon applying the data of 5# anemometer tower for the complete year from 1 November 2017 to 31 October 2018 in this paper, authors not only simulate the wind flow at 5# anemometer tower by using WAsP software prior to extending to the entire project field, but also calculate the error for power generation and actual power generation of wind farm through making a comparison for values of different wake decay constant to evaluate the value range applicable to the wake decay constant for this project.

The daily mean vertical temperature gradient was calculated using annual temperature data collected at the heights of 90 m and 10 m of the Xutuozi anemometer tower, and the atmospheric stability classification was performed using the calculated results. The frequency of wind farm atmospheric stability is D (neutral) is 37.16%, E&F (stable group) is 36.61%, and the total frequency of wind farm atmospheric stability is neutral and stable is 73.77%. (Figure 3). It is possible to conclude that the overall atmospheric stability of Xutuozi Wind Farm is stable. When the atmosphere is neutral and stable, the wake after the wind turbine has a broader range of influence, and the wind speed recovers more slowly after the wake.

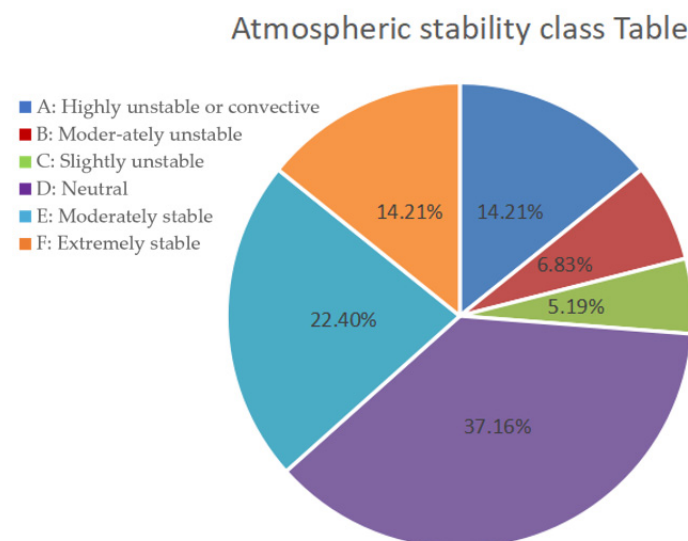


Figure 3. Xutuozi Wind Farm's atmospheric stability classification.

The WAsP software was used to analysis the wind speed and wind direction, and the comparison was made by comparing the wake flow loss from SCADA data and simulated wake flow loss by using different wake decay constant. During the evaluation, the annual average wind speed of 5# tower at the height of 100 m is 6.7 m/s. Under the same roughness, the Annual energy production (AEP) and the wake loss under different wake decay constant (WDC) are shown in Table 3. The error represents the difference between the simulated wake and the actual wake. The maximum deviation can reach 40.44% when the wake decay constant is 0.075, and the minimum deviation is 1.27% when the wake decay constant is 0.035. A low WDC indicates that the wind speed recovers slowly after wake.

Table 3. AEP and wake loss by different WDC of Xutuozi Wind Farm.

WDC	AEP(GWh)	Wake Loss	Error
0.03	704.08	14.77%	10.80%
0.035	714.57	13.50%	1.27%
0.04	720.77	12.75%	−4.36%
0.45	729.11	11.74%	−11.93%
0.05	735.47	10.97%	−17.71%
0.055	741.09	10.29%	−22.81%
0.06	748.03	9.45%	−29.11%
0.065	752.65	8.89%	−33.31%
0.07	756.70	8.40%	−36.99%
0.075	760.50	7.94%	−40.44%

As well known that a reasonable turbine arrangement scheme can reduce wake loss and increase power generation, wake loss is an important criterion for evaluating whether the arrangement scheme is reasonable. Using WAsP to simulate the wake flow loss for each sector. According to the simulation results, the wake flow loss in 90 and 270 sectors can reach up to 30%. (Figure 4). Figure 4 shows that the wake loss is small in the sector with the main wind direction with observation (obs.) wake is 7.44%, but it is greater in the sector with the crosswind direction with observation (obs.) wake is 36.85%. The simulated situation corresponds to the actual trend. It means that the Xutuozi wind farm's layout is reasonable.

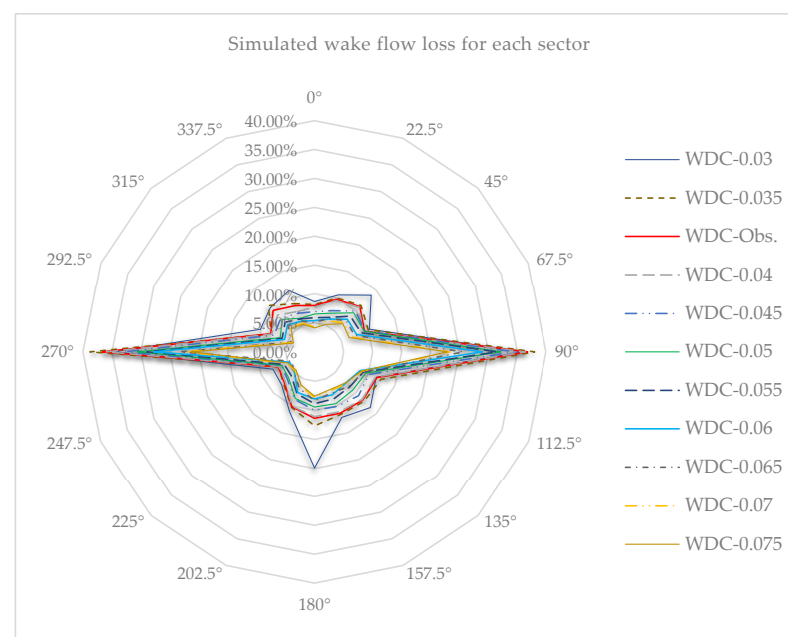


Figure 4. Simulated wake loss for each sector.

When the wind direction is 17 degrees, turbines T1 to T6 are in the same straight line (Figure 5), and the wind direction is close to the main wind direction. To calculate the wake loss of this train of wind turbine generators, choose the time step when the wind direction is 17 degrees and use different wake decay constants. Figure 6 depicts the outcome.

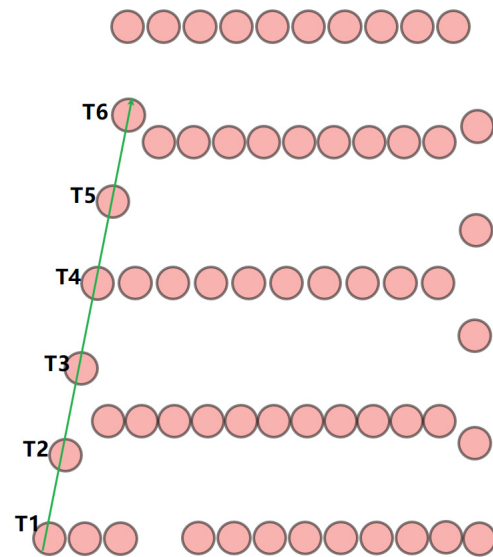


Figure 5. Wind direction is 17-degree.

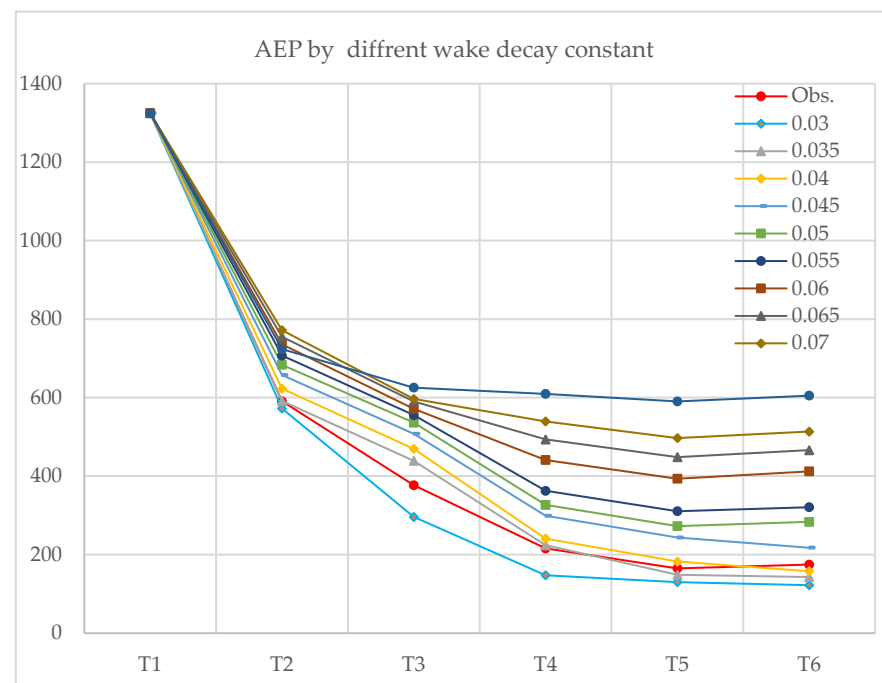


Figure 6. AEP by different wake decay constant when wind direction is 17-degree.

According to the results in Figure 6, the output of the first three turbines drops rapidly and then flattens out. According to the actual output curve, the 6th turbine is slightly less affected by the wake than the 5th turbine. The simulated power generation is closer to the actual power generation when the wake decay constant is between 0.035 and 0.04. Figure 6 shows that when the wake attenuation constant is 0.035, the simulation result is the closest to the actual output (Figure 6, Obs.), with an error of 2.37%.

3.2. Case Study in Yangkou Wind Farm

3.2.1. Case Description

The Yangkou wind farm is located in the South Yellow Sea offshore Nantong City, Jiangsu Province with a planning installed capacity is 400 MW. The project's center is 39 km from the coastline with an ocean area is 90 km². The project belongs to the coastal wind farm and the terrain is simple. There is an 1824# anemometer tower in the project area. The complete annual date of 1824# tower from 1 November 2017~31 October 2018, the annual mean wind speed at altitude 100 m is 7.62 m/s and the main direction is SE as Figure 7, and the mean turbulence intensity at 15 m/s is 0.0767, which is lower than IEC category C. Based on the SCADA data, the wake flow loss for this wind farm is 13.86%, and its annual energy production is 1036.43 GWh. Figure 4 depicts the wind farm layout; the turbine separation distance in the main wind direction is 10 rotor diameters and 3.5 diameters in the crosswind direction. When calculating for this project utilizing WAsP, Parameter settings as shown in Table 1. The WRG in Figure 6 shows that the wind speed gradually increases from the land to the sea. According to the computation, it can be shown that the ocean wind is more stable and has less noticeable variance than the land wind. The WRG in Figure 8 shows that the wind speed gradually increases from the land to the sea. According to the computation, it can be shown that the ocean wind is more stable and has less noticeable variance than the land wind.

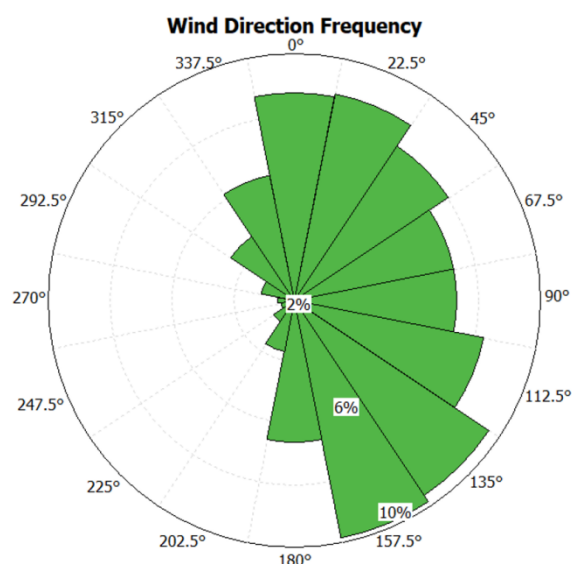


Figure 7. Wind direction rose of 1824#.

3.2.2. Results and Discussions

Through the above-mentioned method of analyzing A wind farm, it simulates the wind energy resources at 1824# anemometer tower by using WAsP based on the data of 1824# anemometer tower. It is able to make a comparison for the results of simulated wake flow and wake flow of wind farm by means of simulating the different wake decay constant.

Figure 9 depicts a classification map of the Yangkou wind farm's atmospheric stability level. The daily mean vertical temperature gradient was calculated using temperature data from the Yangkou anemometer tower at 100 m and 10 m heights, and the atmospheric stability was graded based on the calculated results. Yangkou Wind Farm has a frequency of atmospheric stability of Class C (weak stability) of 21.25%, a frequency of Class A & B (unstable category) of 53.96%, and a total frequency of Class A, Class B, and Class C of 75.21%. As a result, it can be concluded that the atmospheric stability of the Yangkou wind farm is unstable. When the atmosphere is unstable, the turbulence effect is enhanced, which can increase the recovery speed of the wind speed after the wake.

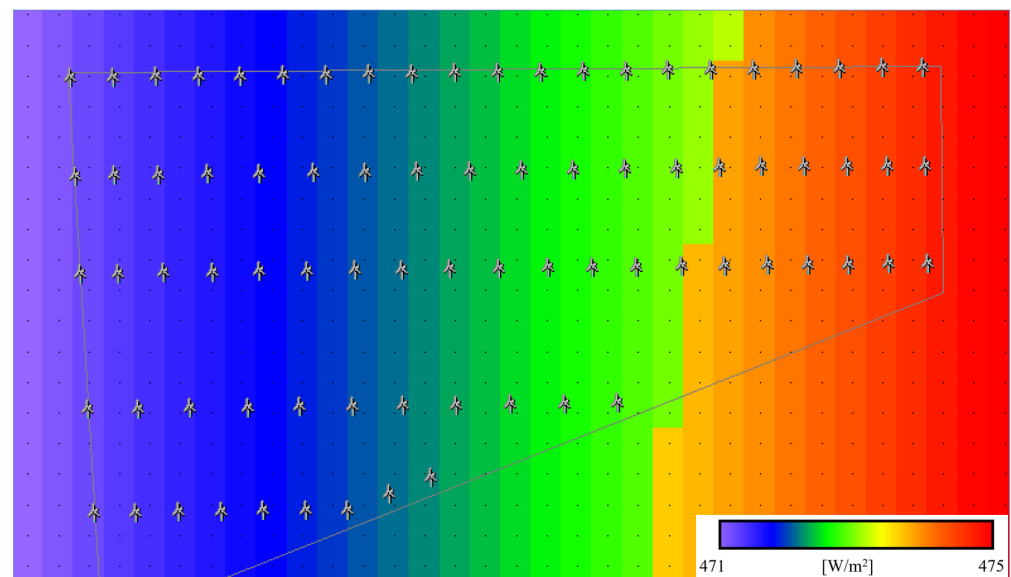


Figure 8. Resource diagram for position of Yangkou wind farm.

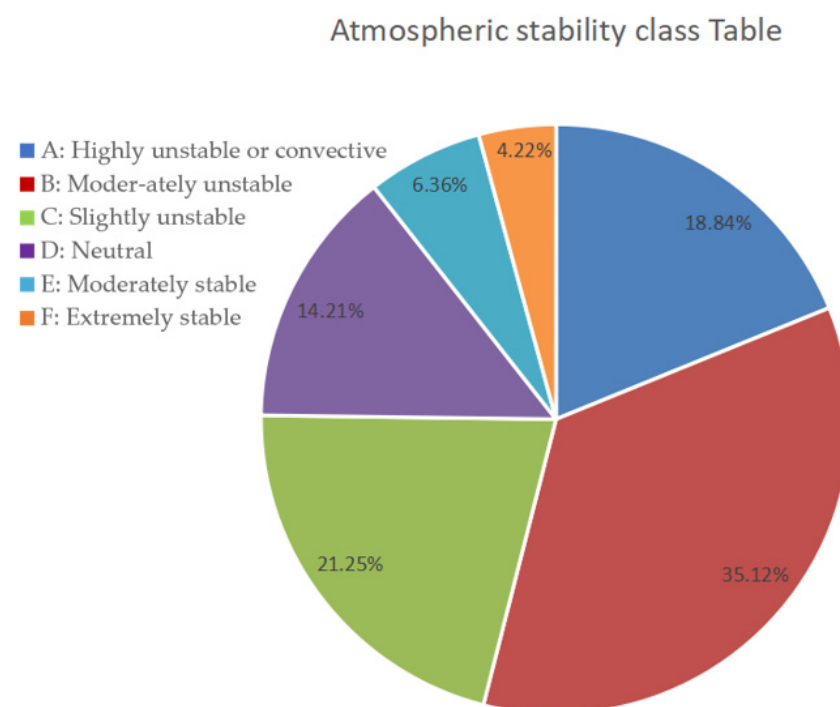


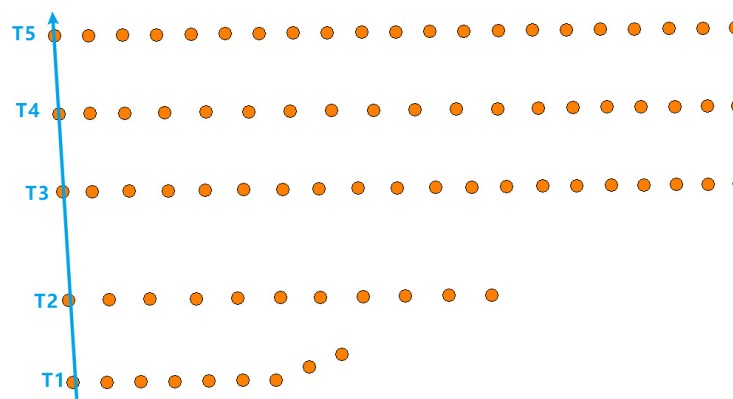
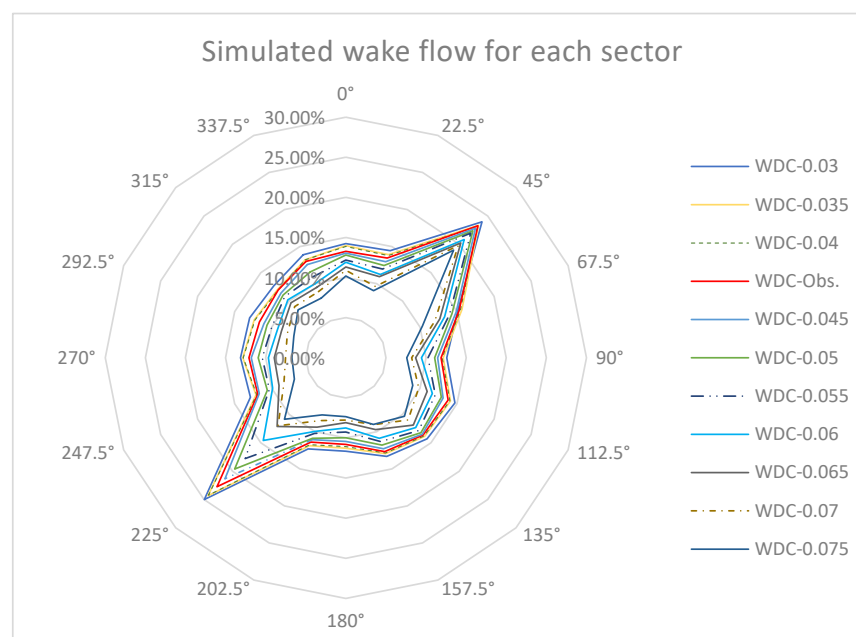
Figure 9. Yangkou Wind Farm's atmospheric stability classification.

Table 4 shows the annual energy production (AEP) and wake loss results using the same roughness value and different wake decay constants (WDC). The difference between the simulated and actual wake is represented by the error. When the wake decay constant is 0.075, the maximum deviation is 33.46%; when it is 0.04, the minimum deviation is 0.42%. The WDC value of this wind farm is also relatively low, but slightly higher than that of Xutuozi Wind Farm, indicating that the recovery of wind speed after the wake is faster than that of Xutuozi Wind Farm.

Table 4. AEP and wake loss by different WDC of Yangkou Wing Farm.

WDC	AEP(GWh)	Wake Loss	Error
0.03	1024.85	14.82%	6.94%
0.035	1030.23	14.38%	3.72%
0.04	1035.73	13.92%	0.42%
0.45	1041.21	13.46%	−2.86%
0.05	1048.10	12.89%	−7.00%
0.055	1055.64	12.26%	−11.52%
0.06	1064.90	11.49%	−17.07%
0.065	1073.98	10.74%	−22.52%
0.07	1082.60	10.02%	−27.68%
0.075	1092.23	9.22%	−33.46%

The wind direction is close to the main wind direction when the wind direction is 358 degrees (Figure 10), the blue arrow is the direction. Calculate the wake loss for the wind turbine with the wind direction of 358 degrees using different wake decay constant using the same method as above. Figure 11 depicts the end result.

**Figure 10.** Wind direction is 358-degree.**Figure 11.** Simulated wake loss for each sector.

The wake loss of turbines in this column is calculated at different value of the wake decay constant. Figure 9 shows that wake loss in the main wind sector is not the lowest. The 225-degree sector has the greatest wake loss, followed by the sector adjacent to the NE secondary main wind direction. The wake flow in the 315-degree sector is kept to a minimum with observation(obs.) wake is 10.81%, whereas the wake loss in the 135-degree sector in the main wind direction is relatively high with observation wake is 13.62%, indicating that the wind farm's layout scheme needs to be optimized.

The output of the first three turbines drops rapidly and then flattens out, as shown in Figure 4. When the wake decay constant is between 0.03 and 0.04, the simulated power generation is closer to the actual power generation. Figure 12 shows that when the wake decay constant is set to 0.04, the simulation result is the closest to the actual output (Figure 12, Obs.), with an error of 1.02%.

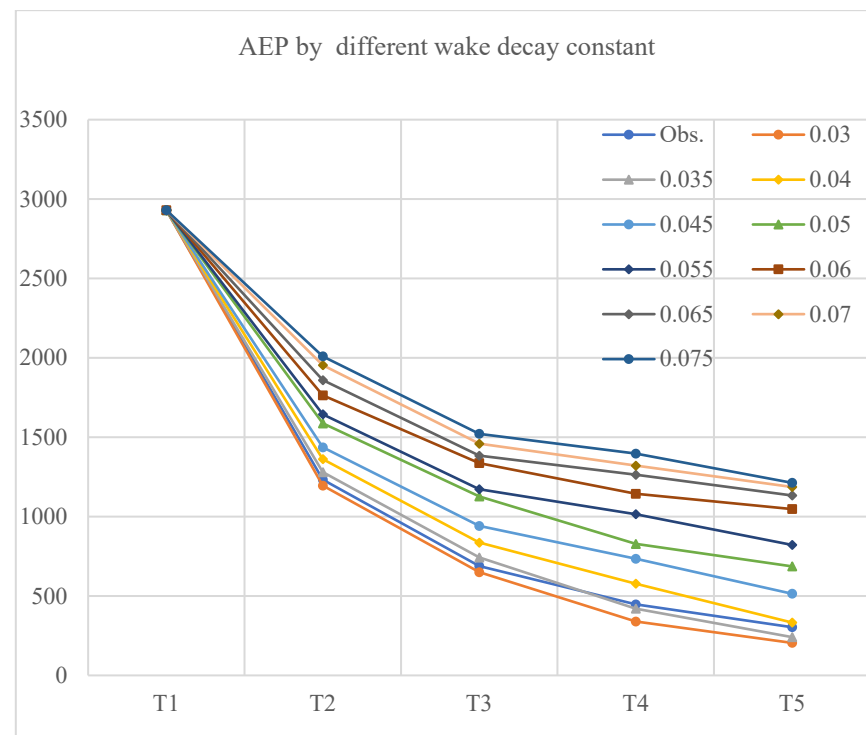


Figure 12. AEP by different wake decay constant.

4. Conclusions and Prospects

This paper compares the measured wake data of the wind farm with the simulated wake results under different wake decay constant. Based on WASP, the necessity of reasonable selection of wake decay constant considering regional wind resources is verified, and the range of wake decay constant applicable to offshore wind farms in eastern coastal areas of China is obtained. The following conclusions can be made by the comparison and suggestion:

- (1) Because coastal wind farms have relatively simple terrain, WASP can be used to simulate the entire wind farm. The engineering application examples in this paper demonstrate that the wake attenuation constant used by WASP's recommended PARK model is too high. The maximum prediction error exceeds 40% when using the recommended value to calculate the power generation of the Yellow Sea wind farm. The error in calculating the annual power generation of the wind farm is less than 5% when the value of the wake decay constant is controlled between 0.03 and 0.045. When using the Park wake model to simulate wind farms in WASP, the wake attenuation constant has a significant impact on the simulation results. So, engineers should conduct a thorough analysis of the local wind resources and environment before

deciding on a more reasonable wake decay coefficient. We only use two wind farms for verification in this paper, which can provide reference but not statistical significance. In future work, we will use more real-world projects for verification analysis to broaden its reference value.

- (2) In this study, two wind farms are located in the Yellow Sea. The value of the wake decay constant in Xutuozi offshore wind farm is slightly lower than that in Yangkou wind farm. The Xutuozi Sea Wind Farm in the Yellow Sea's northwest is higher than 20 km offshore, with an island about 5 km WSW. Because the Xutuozi Wind Farm's main wind direction is north, the small island has no discernible impact on the wind farm. More importantly, the western Yellow Sea is a semi-inland water body located between the Korean Peninsula and the Liaodong Peninsula. Yangkou Wind Farm is 39 km offshore in the South Yellow Sea, which connects to the East China Sea at the Yangtze River's mouth. The geographical environment also has a significance impact on the value of the wake decay constant.
- (3) The Xutuozi wind farm is located in north-east China, close to the ocean. It has a temperate monsoon climate as well as an oceanic climate. The summer monsoon in the projected area will be less intense than in the south. As a result, temperature advection is weaker. In comparison to the south, the formed atmospheric knot is not conducive to vertical movement. The cold air flow from Siberia will have a difficult time reaching (Da Lian) Xutuozi. The climatic conditions described above show that the atmosphere in the project area is more stable than that in the southern region throughout the year, confirming the statistical results of measured data.
- (4) Yangkou Windfarm is located in Jiangsu Province's southeast coast, which has a sub-tropical Marine monsoon climate. The warm advection intensity is greater in comparison to the summer monsoon in northern China, and the lower atmosphere is heated up more frequently. As a result, vertical movement is evident in Yangkou, and the atmosphere is unstable in comparison to that of northern China. Furthermore, the presence of enough water vapor in the southern atmosphere provided unstable energy for the vertical motion of the atmosphere, exacerbating atmospheric instability in the Yangkou wind farm.
- (5) The value of the wake decay constant related to atmospheric stability. When atmospheric stability is unstable, the turbulent energy in the unstable boundary layer increases, and the wind shear influenced by weather increases. The energy exchange between the area and the external free-stream wind is faster, and the distance for the wind speed after the wake of the wind turbine to return to the free-stream wind speed is shorter. When the atmosphere is neutral or stable, the wind shear is smaller, the wind speed after the wake of the wind turbine returns to the free-flow wind speed is slowly, and the influence distance of the wake increases. Taking into account the influence of atmospheric stability on the wake, appropriately increasing the value of wake decay constant when the atmosphere is unstable and appropriately decreasing the value of wake decay constant when the atmosphere is neutral and stable can improve the accuracy of power generation calculations.
- (6) China's offshore wind resources are plentiful, but their temporal and spatial characteristics, as well as their distribution, remain unknown. It is necessary to conduct wind resource measurement and evaluation in this direction.
- (7) In order to promote the development of offshore wind power, more evaluation methods must be introduced, as well as more examples to verify and summarize.

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