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Wind Speed Characteristics and Wake Effect Calculation of Wind Farms in Central Inner Mongolia (Postprint)

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Abstract

To investigate the wake characteristics of wind farms and their relationship with meteorological conditions, 33 wind turbines from a wind farm in central Inner Mongolia were selected to statistically analyze wind resource assessment parameters including average wind speed, wind direction, and wind frequency distribution from 2021 to 2023. Based on the Jensen wake model, wind speeds in the wake region under different wind directions and refined prevailing wind directions were calculated, and the correlation between wind speed considering wake effects and other meteorological elements was explored. The results show that: (1) From 2021 to 2023, the wind farm in central Inner Mongolia was dominated by southwest (SW) winds, with high-frequency wind directions shifting from westerly to southerly within the year; wind directions were concentrated within months with small wind speed differences. The average wind speed was highest under prevailing wind directions, and the wind speed frequency curve exhibited a positively skewed distribution. (2) Under average wind speeds for each wind direction, the wind speed loss rate of the most wake-affected wind turbines exceeded 10%, with over 50% of wind turbines affected by wake effects under northwest (NW) and southeast (SE) wind directions; wind speed losses were concentrated in the downstream positions toward the northeast (NE) of the wind farm, with more pronounced wind speed reductions under westerly wind directions. (3) Atmospheric pressure, air temperature, and humidity had different degrees of influence on the diurnal variation of wind speed under different wind directions. Under the influence of these meteorological factors on wind speed, the SW wind direction showed relatively better performance of the wake model calculations in the 4–5 $m \cdot s^{-1}$ wind speed interval compared to other wind speed ranges, with the mean absolute percentage error of wind speed being negatively correlated with relative humidity. The NW wind direction showed closer agreement between wake model-calculated wind speeds and measured values in the 9–10 $m \cdot s^{-1}$ wind speed interval, with errors being positively correlated with both atmospheric pressure and air temperature. The SE and NE wind directions showed better performance of wake model calculations in the 9-10 $m \cdot s^{-1}$ and 7-8 $m \cdot s^{-1}$ wind speed intervals, respectively. The research results can provide certain references for wind turbine wake effect analysis and wind farm wind speed prediction.

Full Text

Preamble

To investigate the wake characteristics of wind farms and their relationship with meteorological conditions, this study selected a wind farm in central Inner Mongolia as the research site. Based on multi-year wind resource assessment parameters including average wind speed, wind direction, and wind frequency distribution, statistical analyses were performed on wind turbine groups. The study calculated wind speeds in wake regions for different wind directions and refined prevailing wind directions, and explored correlations between wind speed—accounting for wake effects—and other meteorological factors. The results indicate that: (1) The dominant wind direction shifted from westerly to southerly throughout the year, with high-frequency wind directions showing concentrated monthly patterns and small wind speed differences. The average wind speed was highest in the prevailing wind direction, with the wind speed frequency curve exhibiting a positive skew distribution. (2) Atmospheric pressure, temperature, and humidity had varying degrees of influence on the diurnal variation of wind speed across different wind directions. Wind turbines located downwind experienced more significant wind speed reductions, particularly for westerly wind directions. (3) Under different meteorological factors, the wake model demonstrated relatively better performance in the v wind speed interval compared to other speed ranges. The mean absolute percentage error of wind speed was negatively correlated with relative humidity, while in the v wind speed interval, the model-calculated wind speeds were closer to measured values, with errors positively correlated with both atmospheric pressure and temperature. (4) The wake model performed well in the v and v wind speed intervals. The research findings can provide valuable references for analyzing wind turbine wake effects and predicting wind farm wind speeds. Under the average wind speed for each wind direction, the wind speed loss rate of the most severely affected turbines exceeded v%, with more than v% of turbines experiencing wake effects. Wind speed losses were concentrated in the northeast (v°) direction of the wind farm.

1.3.1 Jensen Wake Model

The Jensen wake model is employed to calculate wind speed deficits downstream of wind turbines. The model assumes linear expansion of the wake and a uniform velocity deficit distribution within the wake cross-section. The fundamental equations governing the wake development are:

$$U(x) = U_0 \left[1 - \frac{2a}{(1 + kx/r_1)^2}\right]$$

where $U(x)$ represents the wind speed at distance x downstream, U_0 is the free-stream wind speed, a denotes the axial induction factor, k is the wake decay constant, and r_1 is the rotor radius. The wake radius at distance x is given by:

$$r(x) = r_1 + kx$$

The model calculates the velocity deficit by considering the momentum conservation within the wake region, providing a simplified yet effective approach for estimating wake losses in wind farm layouts.

1.3.3 Weibull Distribution

The Weibull distribution is utilized to characterize the statistical properties of wind speed frequency. The probability density function $f(v)$ and cumulative distribution function $F(v)$ are expressed as:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right]$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right]$$

where v represents wind speed, k is the shape parameter, and c is the scale parameter. These parameters are estimated through maximum likelihood methods to accurately represent the local wind resource characteristics.

1.3.4 Correlation Analysis

Correlation analysis is performed to quantify relationships between wake-induced wind speed reductions and meteorological variables. Pearson correlation coefficients are calculated to evaluate the linear dependence between model errors and atmospheric pressure, temperature, and humidity. The correlation coefficient r_{xy} between variables x and y is computed as:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

This analysis identifies key meteorological factors influencing wake model accuracy under different wind conditions.

1.3.5 Error Assessment

Model performance is evaluated using standard error metrics. The mean absolute percentage error (MAPE) and root mean square error (RMSE) are calculated to quantify discrepancies between modeled and measured wind speeds:

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{V_{\text{obs},i} - V_{\text{mod},i}}{V_{\text{obs},i}}\right| \times 100\%$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{\text{obs},i} - V_{\text{mod},i})^2}$$

where V_{obs} and V_{mod} represent observed and modeled wind speeds, respectively. These metrics provide comprehensive evaluation of model accuracy across different wind speed intervals and directions.

2.1.1 Wind Direction Analysis

Wind direction characteristics are analyzed using data from the meteorological mast. The wind rose diagram [Figure 5: see original paper] illustrates the frequency distribution of wind directions, revealing the dominant patterns at the site. The analysis shows that southwesterly winds prevail throughout the year, with seasonal variations causing shifts in the primary wind direction. Monthly analysis indicates that wind directions are more concentrated within individual months, while annual patterns show a broader distribution. The relationship between wind direction and wake interaction is examined by mapping turbine positions relative to frequent wind azimuths.

2.1.2 Wind Speed Analysis

Temporal variations in mean wind speed are characterized for different wind directions using anemometer tower data. Figure [Figure 6: see original paper] presents the diurnal and seasonal patterns, showing that wind speeds generally peak during daytime hours and exhibit distinct seasonal cycles. Probability density functions of wind speed for each direction are plotted in [Figure 7: see original paper], demonstrating that the Weibull distribution effectively captures the statistical properties. The shape and scale parameters vary by wind direction, reflecting the influence of local terrain and atmospheric stability on the wind resource.

2.2.2 Refined Wake Region Wind Speed

Detailed wake calculations are performed for prevailing wind directions at 10° intervals. The Jensen model is applied to compute wind speeds across the wind farm for incoming wind speeds of 5 $\text{m} \cdot \text{s}^{-1}$ and 8 $\text{m} \cdot \text{s}^{-1}$, as shown in [Figure

8: see original paper]. The analysis reveals spatial patterns of wake losses, with downstream turbines experiencing velocity deficits of up to v% under certain conditions. Table summarizes the maximum wind speed loss rates for different wind directions, quantifying the most severe wake impacts. Further refinement at 10° increments around the prevailing direction [Figure 9: see original paper] demonstrates the sensitivity of wake losses to small changes in wind azimuth, highlighting the importance of precise wind direction data for accurate wake modeling. The results show that turbines in the northeast sector of the farm experience the most consistent wake effects due to the prevailing southwesterly winds.

2.2.3 Correlation Analysis with Meteorological Factors M

Figure 10 [Figure 10: see original paper] presents the daily variations of wind speed and major meteorological factors recorded at the anemometer tower. Table 2 shows the correlation of daily variations between wind speed and major meteorological factors across different wind directions. Table 3 and Table 4 quantify the error percentages between wake model predictions and measured wind speeds, along with corresponding meteorological factor values, for SW/NW and SE/NE wind directions, respectively.

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Abstract: To investigate the characteristics of wind farm wake effects and their relationship with meteorological conditions, 33 wind turbines from a wind farm in central Inner Mongolia, China were selected for analysis. Wind resource assessment parameters, including average wind speed, wind direction, and wind frequency distribution, were statistically analyzed from 2021 to 2023. Using the Jensen wake model, wind speeds in the wake area were calculated for different wind directions, with a focus on the refined dominant wind direction. The correlation between wind speeds and meteorological factors, accounting for wake effects, was also explored. The findings are as follows:

(1) From 2021 to 2023, the wind farm in central Inner Mongolia was predominantly influenced by southwest winds. High-frequency wind directions shifted from west to south throughout the year. Monthly wind directions were relatively stable, with concentrated wind directions and small wind speed variations. The average wind speed was highest under the dominant wind direction, and the wind speed frequency curve exhibited a positively skewed distribution.

(2) Under average wind speeds for each direction, turbines most affected by the wake experienced wind speed losses exceeding 10%. More than half

of the turbines were affected by wake effects under northwest and southeast winds, with the most significant losses occurring in the northeasterly downstream positions of the wind farm. Wind speed reductions were particularly pronounced under westerly winds.

(3) The impact of barometric pressure, air temperature, and humidity on daily wind speed variation differed across wind directions. For southwest winds, the wake model performed best in the 4–8 m/s wind speed range, with the average absolute percentage error of wind speed negatively correlated with relative humidity. For northwest winds in the 9–12 m/s range, the wake model calculations closely matched measured wind speeds, with errors positively correlated with barometric pressure and temperature. In addition, the wake model performed well in the 9–12 m/s and 7–10 m/s ranges for southeast and northeast winds, respectively.

These results provide valuable insights into the analysis of wind turbine wake effects and wind speed predictions for wind farms.

Key words: wind farm; wind speed; wind direction; wake effect; meteorological factor

Note: Figure translations are in progress. See original paper for figures.

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