The Impact of Climate Change-Induced Wind Speed Decline on Wind Farm Output

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***Abstract*—The primary energy source for wind farms comes from wind energy, which is directly affected by climatic conditions, making them sensitive to changes in climate patterns over long timescales. Climate change can significantly alter the statistical distribution characteristics of wind speeds, affecting the output of wind power and, consequently, the adequacy of power supply in the grid. The ERA5 meteorological data from 1980 to 2019 for six different climatic regions in China were collected and organized. By combining this data with typical wind turbine power models, the wind power output for each region was obtained. Using linear regression trend analysis, the impact of climate change on average wind speed, wind speed skewness, divergence, and the capacity factor of typical units was examined over a long timescale. Simulation calculations show that the decrease in wind speed over a long timescale has a clear regional distribution characteristic. Despite the general downward trend in average wind speed across China, there are still some regions where wind speed is on the rise. Wind farms in areas with high wind speeds are less affected by decreases in wind speed, while those in medium and low wind speed areas are more sensitive to long-term changes in wind speed.**

Keywords—wind power generation, climate change, capacity factor, adequacy

I. Introduction

Promoting the development of renewable energy represented by wind power is an important measure to implement the national "dual carbon" goals. With the large-scale grid integration of wind power, the primary energy characteristics of the power system and the grid balance mode have undergone significant changes[1], leading to new problems and challenges for power supply security and system balance regulation in the power system. The primary energy source of wind farms comes from wind energy, which is directly affected by climatic conditions and is sensitive to changes in climate patterns over long time scales[2]. Climate change may significantly alter the statistical distribution characteristics of wind speed, change the output of wind power, and thus affect the adequacy of grid supply. Therefore, it is urgent to carry out assessment and analysis of the impact of climate change on wind power output.

Changes in climate patterns over long time scales can alter the distribution of surface temperature, precipitation, and wind speed [3][4]. Observational data of wind speed from a large number of ground meteorological stations in China and the Northern Hemisphere indicate that the annual average wind speed at most stations shows a downward trend over long time scales [5][6][7][8]. Overall, this change in wind speed has certain regional characteristics, with average wind speeds generally declining in the mid-low latitude zones while slightly increasing in high latitude areas. Additionally, some individual coastal stations have observed an increase in wind speed [9][10]. Research in the field of meteorology believes that changes in the surface roughness coefficient, mesoscale circulation changes caused by phenomena such as El Niño, and the fact that the warming rate in the polar cold regions is much higher than that in the mid-low latitude areas are all factors contributing to the change in wind speed over a long time scale [11].

In response to the above issues, the article collected and organized ERA5 meteorological data from 1980 to 2019 for six different climate regions in China, combined it with a typical wind turbine power model to obtain the wind power output for each region, and used linear regression trend analysis to examine and analyze the impact of climate change on the average wind speed, wind speed skewness, divergence, and the capacity factor of typical units over a long time scale.

II. Wind Power Capacity Factor Sequence Conversion

A. ERA-5 Database

Previous studies on wind power output have used actual measured wind speed data from meteorological stations;

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although the measured data are reliable in terms of authenticity, there are issues such as low measurement density and the inability to accurately extrapolate measured wind speeds to the wind turbine hub heights due to the influence of the terrain at the measurement points. Meteorological reanalysis data, on the other hand, integrates actual measurements from meteorological stations, satellite remote sensing, numerical model simulations, etc., and is more suitable for broad-scale, wide-area wind power output analysis.

ERA5 (ECMWF Reanalysis v5) is the fifth-generation atmospheric reanalysis dataset of global climate from January 1950 to the present, produced by ECMWF (European Centre for Medium-Range Weather Forecasts), which features fine spatiotemporal resolution and covers a higher range of data altitudes. A study compared ERA5 with MERRA-2 and found that the former performs better in modeling individual generators or wind resources and has more detailed spatiotemporal resolution (1 hour, 0.25°*0.25°) compared to other meteorological analysis data. Therefore, this paper uses data from the ERA5 database from 1980 to 2019, including the north component wind (wind) and east component wind (wind) at 100m altitude, with each grid's wind speed U expressed as:

$$U = \sqrt{\mathrm{u}^2 + v^2} \tag{1}$$

Wind turbines are often installed in mountainous areas at high altitudes, and when assessing wind resources[12], it is necessary to convert the wind speed observation data to the corresponding height of the wind turbine hub. The wind speed changes with height near the ground and is commonly described by an exponential law that characterizes the variation of wind speed with height:

$$V_2 = V_1 * (h_2 / h_1)^{\alpha} \tag{2}$$

where is the wind speed at 100m altitude, is the altitude of the wind farm,is the wind speed at the altitude of the wind farm, is the shear coefficient, also known as the surface roughness index, which reflects the impact of ground roughness on the wind speed profile.

B. *Wind Speed Distribution Model*

Wind speed distribution can well reflect the main characteristics of the wind energy resources at an observation station. For convenient and accurate assessment of the potential and characteristics of wind energy resources at a specific site, the random wind speeds over a period of time can be expressed using a probability density function (PDF), and the distribution parameters are of significant reference value for wind resource assessment and wind turbine selection. Currently, there are various probability density function models describing wind speed distribution, such as Pearson curve fitting, Gamma distribution, lognormal distribution, two-parameter Weibull distribution, and Rayleigh distribution, etc.

The Weibull distribution can fit both near-surface and high-altitude wind speed distributions[13]. When using meteorological observation data to assess wind resources, calculations are generally done in conjunction with the Weibull statistical distribution and the power curve of typical units. The article chooses a Weibull distribution with shape parameter k=2, i.e., fitting Rayleigh measured wind speeds. The expression for Rayleigh's probability density function and cumulative distribution function (CDF) are shown as (3) and (4):

$$f_R(v) = \frac{2v}{c^2}\exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{3}$$

$$F_R(v) = 1 - \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{c}\right)^2\right] \tag{4}$$

C. *Wind Turbine Wind Speed-power Curve and Modle*

For a specific wind turbine selected for a wind farm, the annual electricity production for that unit can be calculated by integrating the local wind speed statistical distribution with the power characteristic curves provided by the manufacturer. This is done by calculating the electricity generation for each wind speed interval based on the duration of that wind speed and the corresponding power curve.

Wind speed frequency distribution is usually divided into intervals of 1 m/s, and the frequency of wind speeds within each interval is tallied. The International Energy Agency recommends the use of the Bins method for mathematical fitting based on statistical analysis of wind speed data, with the Rayleigh wind speed distribution model being used for wind frequency distribution.

Annual energy production (AEP) can be estimated using the measured power curve of the turbine and the wind speed frequency distribution (Rayleigh). The calculation formula is as follows (5):

$$AEP = N_h \sum_{i=1}^{N}\left[F(v_i) - F(v_{i-1})\right]\left(\frac{F(v_i) - F(v_{i-1})}{2}\right) \tag{5}$$

The annual energy production (AEP) can be estimated using the actual measured power curve of the wind turbine and the Rayleigh frequency distribution of wind speeds. The is calculated as the sum of the product of the number of hours in a year (8760 hours) with the power output corresponding to the average wind speed of each wind speed interval (bin), adjusted according to the Rayleigh distribution. The number of bins (N) is determined by the wind speed frequency distribution.

III. METEOROLOGICAL LOCATION INFORMATION

Wind power development in China has been mainly concentrated in the "Three North" regions, which are known for their abundant wind resources. In recent years, as the "dual carbon" goals (carbon peak and carbon neutrality) have been implemented, regions with relatively scarce wind resources, such as South China, have also seen rapid growth in wind power capacity. To explore the impact of wind speed variations in different wind resource levels, research and analysis have been conducted in areas with favorable wind conditions selected from Xinjiang, Gansu, Hebei, Northeast China, Hunan, and Guangxi..

To eliminate the influence of changes in the surrounding landscape on the analysis of long-term changes in extreme wind speeds, the study selected locations with no significant environmental changes and complete data records. These locations include Alashankou in Xinjiang, Liupanshan in Gansu, Lake Chagan in Hebei, Changbaishan in Northeast China, Jinfoshan in Hunan, and Shiwandashan in Guangxi for analysis. Among these, Alashankou is located in the desert and Gobi; Lake Chagan is in a national nature reserve where new construction is prohibited; Liupanshan, Changbaishan, Shiwandashan, and Jinfoshan are in remote mountainous areas, far from populated areas.

IV. Long-term Wind Speed Variation Analysis

A. Analysis of Average Wind Speed Changes Based on Linear Regression

Linear regression can be used to quantitatively analyze whether the trend characteristics of a wind speed series over a certain period are significant. The linear regression line is represented as y = a*x + b, where a and b are regression coefficients. The sign of the regression coefficient b corresponds to an increasing or decreasing trend in the wind speed series. The significance of the trend is tested using the Pearson correlation coefficient.

The linear trend of average wind speed over the forty years from 1980 to 2019 for various typical regions is illustrated in Figure 1, and the related statistical information about the average wind speed and the rate of change of wind speed for each decade is included in Table 1.

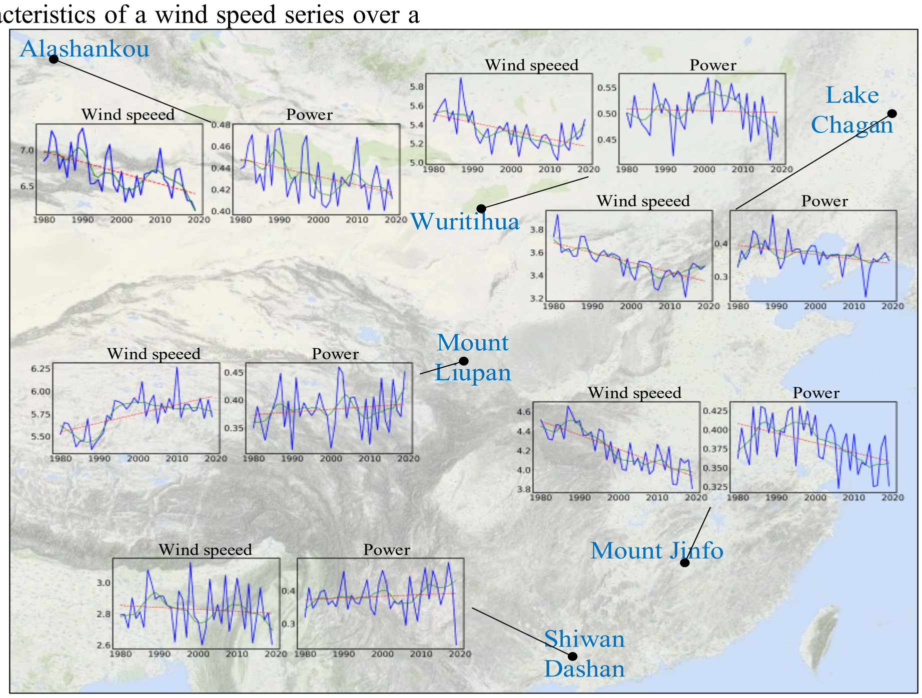


Fig. 1. Long-Term Trends in Annual Mean Wind Speed at Typical Site.

TABLE I. LONG TERM VARIATION OF WIND OF THE INVESTIGATED SITES(MS^{-1}10A^{-1})

	Wuritihua	**Mount Liupan**	**Lake Chagan**	**Mount Jinfo**	**Alashankou**	**Shiwan Dashan**
1980s	5.701	3.96	4.460	3.564	6.013	2.848
1990s	5.411	4.07	4.338	3.411	5.935	2.855
2000s	5.410	4.22	4.184	3.323	5.813	2.803
2010s	5.305	4.19	4.187	3.311	5.839	2.814
change rate(%)	-6.956*	5.853*	-6.130*	-7.093*	-6.144*	-1.188
R	0.31	0.36	0.53	0.63	0.36	0.01

As shown in Figure 3 and Table 1:

The average wind speed in Alashankou, Lake Chagan, Changbai Mountain, and Jinfoshan regions shows a clear downward trend, with an average reduction rate of over 6% over 40 years.

The Shiwandashan area has the lowest average wind speed and the smallest annual average wind speed trend, with a downward trend only in the early 1990s, while in other periods, the average wind speed fluctuates near the mean. Among them, the Jinfoshan area has the most significant downward trend, with an average wind speed reduction of 7.093%.

The Liupan Mountain area shows an upward trend in average wind speed. Between 1988 and 1994, the average wind speed in the Liupan Mountain area continued to rise, reaching 5.900 ms-1 on average in 1994, and thereafter fluctuated around 5.8 ms-1.

B. Decadal Changes in the Statistical Distribution of Wind Speed

In addition to the annual average wind speed, the statistical characteristics of wind speed can also reflect its trend. The following divides the survey period into four decades (1980-1989, 1990-1999, 2000-2009, and 2010-2019), calculates the skewness and kurtosis for each period (as shown in Table 2), and plots the cumulative distribution functions of wind speed for each decade as shown in Figure 2.

TABLE II. ANNUAL SKEWNESS AND DISPERSION OF WIND SPEED AT TYPICAL SITES BY ERA

	1980s		**1990s**		**2000s**		**2010s**	
	kurtosis	**skewness**	**kurtosis**	**skewness**	**kurtosis**	**skewness**	**kurtosis**	**skewness**
Alashankou	1.29	1.14	1.27	1.10	1.10	1.08	1.51	1.13
Mount Liupan	0.12	0.50	0.03	0.50	0.21	0.55	0.24	0.53
Lake Chagan	0.48	0.77	0.68	0.84	0.59	0.83	0.52	0.80
Wuritihua	-0.03	0.33	0.02	0.33	-0.06	0.33	0.07	0.39
Mount Jinfo	0.08	0.45	0.01	0.48	-0.02	0.45	-0.01	0.43
Shiwan Dashan	1.71	6.76	1.57	6.34	1.84	6.75	1.74	6.95

The Cumulative Distribution Function (CDF) is a function used in probability theory and statistics to describe the probability distribution of a real random variable. The cumulative distribution graph of wind speed allows us to visually observe the concentration of different wind speeds.

Kurtosis measures the thickness of the tails of a data distribution, or the "peakedness" of the distribution. A higher kurtosis value indicates thicker tails in the distribution, suggesting a greater likelihood of outliers.

Skewness measures the asymmetry of a data distribution. A positive skewness value indicates a longer tail on the right side of the distribution, with the bulk of the data shifted to the left; a negative skewness value indicates a longer tail on the left side, with the bulk of the data shifted to the right.

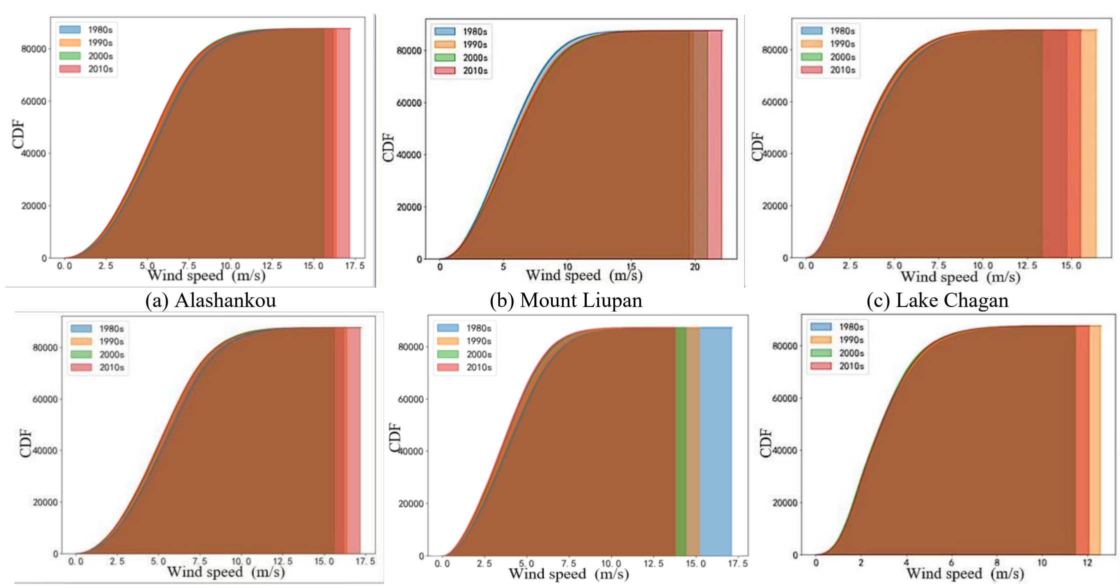
The shape of the CDF is closely related to kurtosis and skewness. The left-right symmetry of the CDF shape corresponds to the positivity or negativity of skewness; the rate of change of the CDF shape around a certain value is positively correlated with the value of the kurtosis. Comparing the charts, it is clear to see:

There are certain decadal differences in the wind speed distribution at Alashankou. The CDF graph shifts to the left, and both kurtosis and skewness are greater than 1, indicating that the region has a higher heavy-tailed effect compared to a normal distribution, with more high wind speed periods and a general reduction in wind speeds over forty years.

The wind speed distributions in Lake Chagan, Changbaishan, and Jinfoshan show very obvious decadal differences. The CDF graphs for all three locations shift to the left, with a general reduction in wind speeds over forty years. Changbaishan and Jinfoshan have kurtosis close to 0 and lower skewness, indicating that the wind speeds in these areas are close to a normal distribution.

The CDF graph for the Shiwandashan area remains largely unchanged, with the wind speed not varying significantly with the decades. With kurtosis greater than 1 and skewness greater than 6, this area has a significant heavy-tailed effect, with wind speeds concentrated above the average.

Among all the sites, the CDF graph for Liupan Mountain shifts to the left, with a general increase in wind speeds over forty years, and both kurtosis and skewness are relatively small, suggesting the data distribution is close to normal.



(a) Alashankou (b) Mount Liupan (c) Lake Chagan

(d) Wuritihua (e) Mount Jinfo (f) Shiwan Dashan

Fig. 2. Decadal probability distribution of investigated site.

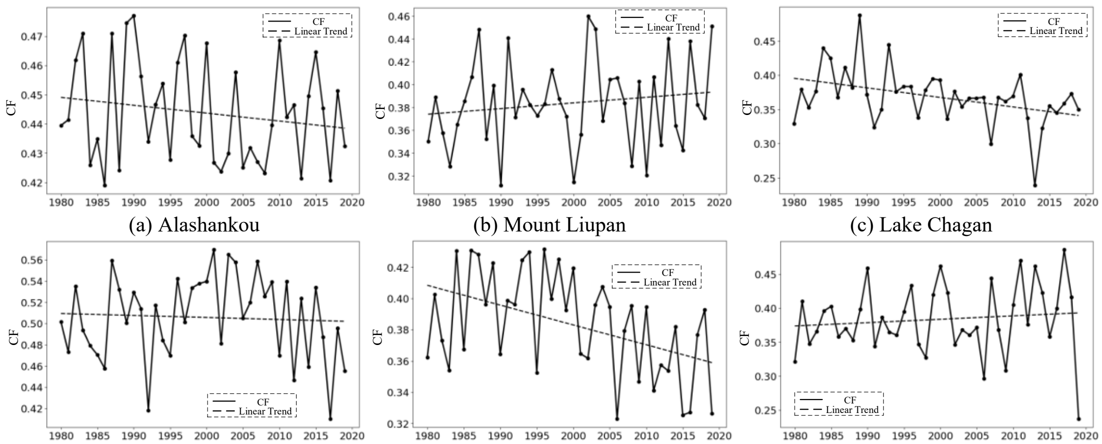
V. The Impact of Climate Change on the Power Output of Generating Units

The capacity factor is a basic indicator for measuring the wind energy utilization efficiency of wind turbines. In this section, it is used to examine the impact of climate change on the energy efficiency of wind power generation units. Its definition is shown in equation (6):

$$CF = E/\left(P_R \times 8760\right) \qquad (6)$$

The formula includes: CF is the dimensionless capacity factor; E represents the actual electricity generation of the wind farm (kWh); PR is the rated power of the wind turbine.

By using the statistical distribution of wind speed over the years and the power curve of the wind turbine, the annual electricity generation data is calculated. Afterward, the changing trend of its capacity factor is plotted as shown in Figure 3. The inter-annual capacity factor and its changing trend, as well as other related information, are detailed in Table 3.



(a) Alashankou (b) Mount Liupan (c) Lake Chagan

(d) Wuritihua (e) Mount Jinfo (f) Shiwan Dashan

Fig. 3. Long term variation of capacity factor(/10a, 1973-2012).

TABLE III. Long Term Variation of Capacity Factor($10a^{-1}$, 1973-2012)

	Alashankou	**Mount Liupan**	**Lake Chagan**	**Wuritihua**	**Mount Jinfo**	**Shiwan Dashan**
1970s	0.446	0.420	0.395	0.500	0.447	0.372
1980s	0.450	0.425	0.374	0.505	0.458	0.384
1990s	0.435	0.430	0.359	0.536	0.430	0.375
2000s	0.444	0.429	0.335	0.482	0.381	0.403
Overall rate of change	-1.365*	2.261*	-12.653**	-1.371*	-14.576**	6.805

Comparing Figures 1 and 3, it can be observed that:

The capacity factors of different regions do not completely coincide with the inter-annual variation characteristics of the average annual wind speed.

In the regions of Alashankou, Changbai Mountain, Jinfo Mountain, and the Wanda Mountains, the average wind speed has decreased by about 6% over the past forty years, but the capacity factors in Alashankou and Changbai Mountain areas have remained largely unchanged, whereas the capacity factors in the Jinfo Mountain and Lake Chagan areas have decreased significantly.

In the Liupan Mountain and Wanda Mountains areas, the trends of the average annual wind speed and capacity factors are basically consistent: Liupan Mountain area shows a certain upward trend in the average annual wind speed, and its capacity factor correspondingly increases; the average annual wind speed and capacity factor in the Wanda Mountains fluctuate around the average value.

Compared to the significant decrease in the CF in the Jinfo Mountain and Lake Chagan areas, the CF in Alashankou and Changbai Mountain areas does not show an obvious trend of change under the same wind speed variation. A further comparison of their average wind speeds reveals that the average wind speeds in Alashankou and Changbai Mountain areas are higher (both above 5m/s), while those in Jinfo Mountain and Lake Chagan are lower (Jinfo Mountain is 3.40m/s, Lake Chagan is 4.29m/s). Compared to regions with low wind speeds, regions with high wind speeds have higher "robustness" against changes in average annual wind speed.

VI. Conclusion

The article selects meteorological observation data from six regions for analysis and finds that:

Climate change has caused a relatively obvious downward trend in wind speed over a long time scale. To ensure the adequacy of the power grid of the new type of electric power system, it is imperative to take climate change into more significant consideration as new energy sources are integrated into the grid on a large scale.

The decline in wind speed over a long time scale has clear regional distribution characteristics. While there is a general trend of declining average wind speed in China, some areas still show an upward trend in wind speed. These areas could be given priority for the development of wind farms.

Wind farms in high wind speed areas are less affected by the reduction in wind speed, while wind farms in medium and low wind speed areas are more sensitive to long-term changes in wind speed. It may be worth considering the use of low wind speed turbines in areas with lower average wind speeds to mitigate the impact of reduced wind speeds.

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