Uncertainty Analysis of Annual Wind Speed in Northern China and Its Potential Impact on Energy Sector

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Abstract. In this article, the wind energy uncertainty caused by annual wind speed variation in northern China is studied. The research time period is from 1991 to 2020, and the ERA5 reanalysis wind data is used. The uncertainty statistical indicators are the standard deviation percentage and the maximum deviation percentage of the average wind power density. The analysis results show that the uncertainty of wind energy in Qinghai, Xinjiang, Inner Mongolia, Shanxi is relatively large, these areas are more likely to experience large fluctuations of wind power. Among them, the standard deviation percentage of Qinghai and Xinjiang accounts for 15%-30% or higher. The maximum deviation percentage of Qinghai, Xinjiang, Inner Mongolia, Shanxi accounts for 30%-60% or higher. In addition, the empirical orthogonal function analysis (EOF) results show that there is an anti-phase mechanism of local wind energy fluctuations in Northern China, especially between the Northeast and Northwest regions, which implies that the power transmission between the Northeast and Northwest regions is helpful to reduce the wind energy uncertainty effect.

1. Introduction
Northern China region includes Beijing, Tianjin, Hebei, Shandong, Shanxi, Shaanxi, Heilongjiang, Jilin, Liaoning, Inner Mongolia, Xinjiang, Gansu, Qinghai, and Ningxia. These areas are the main production areas of wind energy in China. Wind speed has fluctuations, resulting in wind energy output also fluctuating. At present, the energy sector is mainly concerned with short-term wind fluctuation[1]. However, the average annual wind speed also has great fluctuation and potential impact. The annual fluctuation often causes large windy years and small windy years, which generates considerable uncertainty of annual wind power. In addition, there may be fluctuation correlations between different regions. If this phenomenon can be utilized, and an annual cross-region power dispatch plan can be formulated in advance, it will help to reduce the impact of annual wind speed fluctuations, and the energy storage capacity can also be reduced. Therefore, it is of great significance to understand the uncertainty of the annual average wind speed and the fluctuation correlation between different regions.
This paper studied the wind energy uncertainty (80m height) in Northern China from 1991 to 2020 based on ERA5 reanalysis data. The uncertainty statistical indicators are the standard deviation percentage and the maximum deviation percentage of the average wind power density. In addition, in
view of the fluctuation correlation of wind power density between different regions, the Empirical Orthogonal Function analysis (EOF) method is used to analyze the annual average wind power density. Data and methods are introduced in Section 2, and the analysis results are shown in Section 3.

2. Data and methods

2.1. Data

The reanalysis data uses the atmospheric numerical model and assimilation system to absorb the observation data and yield the gridded spatiotemporal data, which is often used as a substitute observation data. It provides an important data source for the research and development of applied technology. Currently commonly used reanalysis data include ERA5 and ERA-Interim of the European Center for Medium-Term Weather Forecast (ECMWF), JRA55 of the Japan Meteorological Agency (JMA), MERRA2 of National Aeronautics and Space Administration (NASA), etc. Among them, ERA5 reanalysis data has the highest resolution which reaches a spatial horizontal resolution of 31km (about 0.25°) and resolution of 1 hour[2,3]. This paper uses the wind speed data at 10m height for research, and pushes it to 80m height through the exponential profile[4], which is

\[
V_{80} = V_{10} \left(\frac{80}{10}\right)^{1/7}
\]

The wind power density \(P_{80}\) at 80m height is[5]

\[
P_{80} = \frac{1}{2} \rho V_{80}^3
\]

Where \(\rho\) is taken as the standard air density of 1.225 kg/m³. This article will mainly study the annual average characteristics of \(V_{80}\) and \(P_{80}\), and the study area covers Northern China, as shown in Figure 1.

![Schematic diagram of the study area](image)

**Figure 1.** Schematic diagram of the study area

2.2. Methods

2.2.1. Standard deviation percentage and maximum deviation percentage

Annual average wind power density \(\bar{P}_j\) is the average of wind power density at all times of a certain year (next we will replace \(P_{80}\) above with \(P_{j,i}\) below), which is

\[
\bar{P}_j = \frac{1}{N} \sum_{i=1}^{N} P_{j,i} \quad i = 1, 2, 3, L \quad N. \quad j = 1991, 1992, L \quad 2020.
\]

Where \(i\) is a certain time in the year, \(N\) is the total number of all times in the year, and \(j\) is a certain year.

We use the standard deviation percentage and the maximum deviation percentage of average wind power density to measure the uncertainty, where the standard deviation percentage \(\bar{P}_{std}\) is the multi-year standard deviation divided by the multi-year average wind power density, which is
\[
P_{\text{std}} = \sqrt{\frac{1}{30} \sum_{j=1991}^{2020} (\bar{P}_j - \frac{1}{30} \sum_{k=1991}^{2020} \bar{P}_k)^2} \times 100\% \quad \text{for} \quad i, j, k = 1991, 1992, L , 2020.
\] (4)

The actual meaning of \( P_{\text{std}} \) is the fluctuation range of the local annual average wind power density.

The maximum deviation percentage \( \bar{V}_{P_{\text{max}}} \) is,
\[
\Delta P_{\text{max}} = \max \left\{ \frac{\bar{P}_j - \frac{1}{30} \sum_{k=1991}^{2020} \bar{P}_k}{\frac{1}{30} \sum_{i=1991}^{2020} \bar{P}_i} \right\} \times 100\% \quad \text{for} \quad i, j, k = 1991, 1992, L , 2020.
\] (5)

The actual meaning of \( \bar{V}P_{\text{max}} \) is the largest fluctuation of the local wind power density once in 30 years.

2.2.2. Empirical Orthogonal Function (EOF) analysis

The EOF method was proposed by Pearson[6]. EOF can decompose regularly or irregularly distributed meteorological fields in time and space to obtain mutually orthogonal spatial distribution modes and their time coefficients. The spatial distribution modes can reflect the spatial distribution characteristics of the target field, while the time coefficient reflects the corresponding changes with time. The EOF method is often used to study the temporal and spatial characteristics of meteorological fields. This method can dig out the typical independent spatial distribution modes hidden in the data, which is helpful for a deeper understanding of the spatial distribution characteristics and their temporal evolution characteristics[7,8].

3. Results

3.1. The average wind speed and average wind power density from 1991 to 2020

As shown in Figure 2, the high value area of annual average wind speed at 80m height is mainly located in Inner Mongolia, Xinjiang, Heilongjiang and other regions, which can reach 5-7 m/s, and the wind power density can reach to 300-400 W/m². In other areas, the wind power is between 50-200 W/m².

![Spatial distribution of average wind speed](image)

![Spatial distribution of average wind energy density](image)

**Figure 2.** Spatial distribution of average wind speed, (a) and average wind energy density, (b) from 1991 to 2020

3.2. The standard deviation percentage and the maximum deviation percentage of the average wind power density from 1991 to 2020

As shown in Figure 3 (a), the standard deviation percentage of most parts of Northern China is between 10%-15%, which means that the annual power generation of wind farms in most areas has an average uncertainty of 10%-15%. Among them, Qinghai and parts of Xinjiang can reach to 20%-30%.
Figure 3. Distribution of the standard deviation percentage (a) and maximum deviation percentage (b) of the average wind power density from 1991 to 2020.

As shown in Figure 3 (b), the largest deviations in most parts of Northern China account for 15%-30%. Among them, parts of Qinghai, Xinjiang, Inner Mongolia, Shanxi, Heilongjiang, and Jilin can reach to 30%-60%, and the local area can reach more than 60%. These areas suffer from great fluctuations once in 30 years.

3.3. EOF modes of average wind power density from 1991 to 2020

The first 6 EOF modal information is shown in Table 1, and all have passed the significance test. Among them, the contribution rate of mode 1, mode 2, and mode 3 all exceed 10%, while the contribution rate of mode 4 does not exceed 10%. Therefore, the first three modes are the dominant modes, and we will focus on these three modes.

Table 1. The first 6 EOF modes information

| Mode | Variance Contribution rate | Cumulative Variance Contribution rate | Eigenvalues | Eigenvalue error range |
|------|-----------------------------|----------------------------------------|-------------|------------------------|
|      |                             |                                        |             | Lower limit            | Upper limit            |
| 1    | 19.0%                       | 19.0%                                  | 102.0       | 101.1                  | 103.0                  |
| 2    | 15.6%                       | 34.6%                                  | 83.6        | 82.8                   | 84.4                   |
| 3    | 10.5%                       | 45.1%                                  | 56.3        | 55.8                   | 56.8                   |
| 4    | 8.3%                        | 53.4%                                  | 44.3        | 43.9                   | 44.7                   |
| 5    | 6.9%                        | 60.3%                                  | 36.8        | 36.5                   | 37.1                   |
| 6    | 4.9%                        | 65.2%                                  | 26.6        | 26.4                   | 26.8                   |

3.3.1. Mode 1

The variance contribution rate of mode 1 is 19.0%, which is the dominant mode of wind energy in Northern China. It can be seen from Figure 4 that the spatial distribution of this mode is relatively consistent, and basically all positive values, indicating that northern China has a uniform trend of change. From the perspective of the time coefficient, there has been a 1-3 year oscillating effect after 2000.

Figure 4. EOF mode 1 of annual average wind power density, (a) spatial distribution, (b) time coefficient.
3.3.2. Mode 2
The variance contribution rate of mode 2 is 15.6%. It can be seen from Figure 5 that the spatial distribution of this mode is not all positive values, but the positive and negative values are interlaced, indicating that the wind energy in northern China has a local anti-phase change mechanism.

![Figure 5. EOF mode 2 of annual average wind power density, (a) spatial distribution, (b) time coefficient.](image)

3.3.3. Mode 3
The variance contribution rate of mode 3 is 10.5%. It can be seen from Figure 6 that the spatial distribution of this mode presents east-west anti-phase characteristics, indicating that Northeast China and Northwest China have opposite wind energy trends. The significance of this discovery is that it can assist the power dispatching department to formulate the power transfer plans between northeast and northwest regions. And such power transfer plans enable the abundant wind power be transferred to the lacking areas, and reduce the wind energy uncertainty effect.

![Figure 6. EOF mode 3 of annual average wind power density, (a) spatial distribution, (b) time coefficient.](image)

4. Conclusions
(1) The standard deviation percentage of average wind power density in most areas is between 10%-15%, which means that most areas have an uncertainty of 10%-15%. And in parts of Qinghai and Xinjiang, it can reach to 20%-30%.
(2) The largest deviation percentage of average wind power density in most areas is between 15%-30%. Among them, parts of Qinghai, Xinjiang, Inner Mongolia, Shanxi, Heilongjiang, and Jilin can reach to 30%-60%, and the local area can reach to more than 60%. These areas suffer from great fluctuations once in 30 years.
(3) The spatial distribution characteristics of EOF mode 2 and EOF mode 3 indicate that there is a local wind energy anti-phase mechanism between Northeast China and Northwest China. The anti-phase mechanism can assist the power dispatching department to formulate the power transfer plans between northeast and northwest regions. And such power transfer plans enable the abundant wind power be transferred to the lacking areas, and reduce the wind energy uncertainty effect.
5. References

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