Research on ecological and climate impacts of offshore wind farms based on remote sensing images

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Abstract

Offshore wind farm (OWF)'s impact on marine ecological environment has attracted widespread attention since its rapid development. The paper uses high-resolution satellite image data to extract the distribution of offshore wind farms (OWFs) in China based on deep learning method. Chlorophyll-a (CHL-a) concentration and sea surface temperature (SST) were used as indicators to analyze the impact of OWFs' development. We can then draw the following conclusions: 1) From 2016 to 2022, the number of OWFs in China continues to increase, the growth rate reachs 28% in 2022. 2) The construction of OWFs presents a development trend from near sea to far sea and from shallow sea to deep sea. From 2016 to 2022, the new OWFs are mainly concentrated in sea areas with 5-50 meters water depth, accounting for 84.7 % of the total increase in OWFs. 3) The distribution density of OWFs is negatively correlated with CHL-a concentration and SST, the more OWFs, the greater the impact on CHL-a and SST. In one word, our work analyzed the development trend of OWFs in China and evaluated the impact of OWFs' expansion on marine ecological environment and climate.

1. Introduction

With the international efforts to cope with climate changes and the increasing consensus on low-carbon energy, the global demand for renewable energy has become increasingly urgent (Chen et al., 2024, Deng et al., 2024, Pooja, 2023, Alharbe and Alluhaibi, 2023, Shivakumar et al., 2019). Due to its advantages on less land occupation, high wind speed, stable performance and large power generation, offshore wind farm (OWF), a kind of renewable energy, is catching more and more attention. (Xu et al., 2020, Best and Halpin, 2019, Wang and Prinn, 2011). Committed to low-carbon transition, China has announced an ambitious goal of reaching its carbon peak by 2030 and achieving carbon neutrality by 2060. The goal is supported by increasing development of renewable energy sources, which also leads to rapid expansion of offshore wind farms (OWFs). By the end of 2022, China's cumulative installed capacity of OWFs has exceeded 30 million kilowatts, ranking first in the world for two consecutive years. While OWF has contributed a lot to the global energy transformation, its impact on marine ecological environment and climate still caused concern. Therefore, people then put more efforts on study of its impact (Helen et al., 2014, Cai et al., 2023, Chen et al., 2023).

A considerable amount of research related to the impacts of OWFs' expansion has already been conducted. One part of researches mainly focus on individual species such as birds, bats or mammals (Keith et al., 2023). For example, analysis of seabirds has shown different behavioral responses to wind turbines and the prediction. Besides, the risk of collision with wind turbines (Verena et al., 2020) can also lead to different behaviors. Similarly, the migration of bats is also affected (Robin et al., 2021). The other part of studies were related to marine ecosystems and sedimentary organic carbon stocks (Lijing et al., 2024, Knut and Esther, 2023). For example, people have studied the effects on phytoplankton and zooplankton, including the 'wave effect', 'shading effect', oxygen depletion and predation pressure (Lijing et al., 2024). Nevertheless, most of the existing researches mainly focused on the impact of marine biodiversity, biological resources, bird ecology, etc. There are still relatively fewer studies on the impact of marine environment and climate (Alves et al., 2023).

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In our work, based on high-resolution satellite remote sensing image data from 2016 to 2022, we extracted China's offshore wind power by using deep learning method. With the extracted data, we can then make analysis on OWFs' expansion speed and its spatial distribution in the past five years. Therefore, we can sort out its change rules. Finally, by combining with the spatial distribution of OWFs, chlorophyll-a and sea surface temperature data, we analyzed the impact of OWFs on the ecological environment and climate. In general, the paper provided with an important basis for offshore wind power expansion analysis and ecological environment impact analysis.

2. Study Area

China is located in the east of Asia, on the west coast of the Pacific Ocean, the China Seas extend from 41°N to the equator with a total area of about 4.73 million km^2. From north to south, four large seas are the Bohai Sea, Yellow Sea, East China Sea, and South China Sea, these seas cover approximately 7.7 × 10^4 km^2, 38 × 10^4 km^2, 77 × 10^4 km^2, 350 × 10^4 km^2 in area, respectively. The research area is shown in Figure 1. The research object of this paper is China 's offshore wind farm from 2016 to 2022. Figures a to j are 10 offshore wind farms distributed in different sea areas, among which two are located in the Bohai Sea, two in the Yellow Sea, four in the East China Sea, and two in the South China Sea. These 10 wind farms are used as research areas to evaluate the impact of offshore wind farms on the marine ecological environment and climate.

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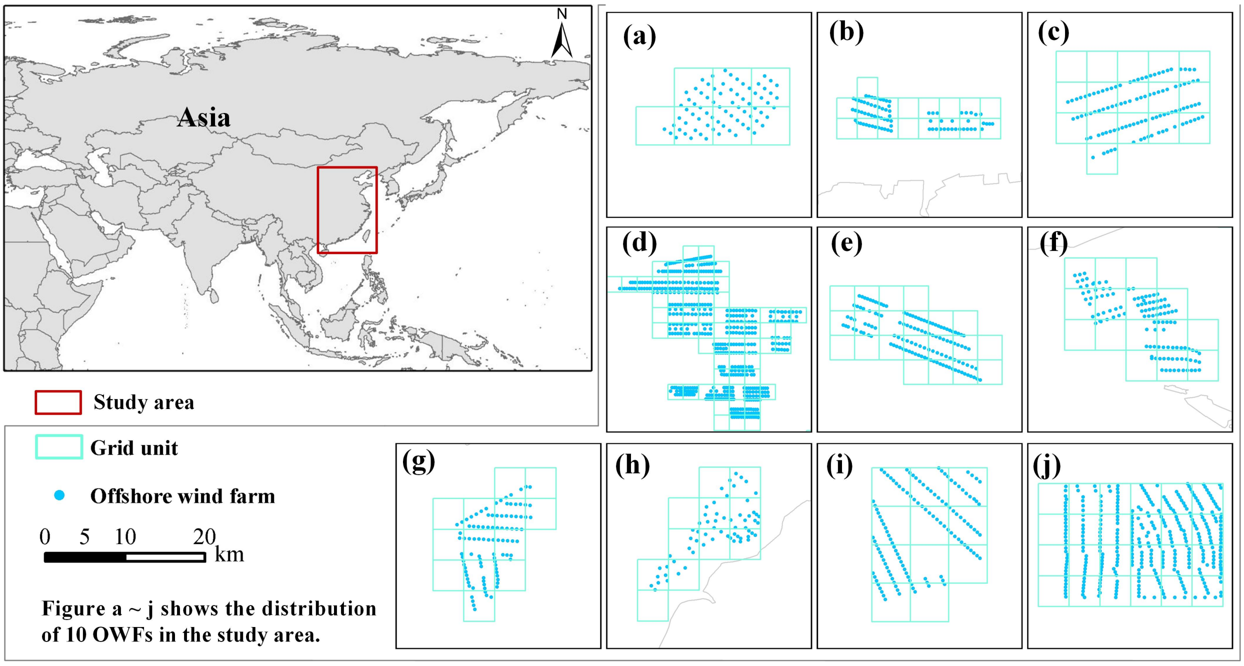

Figure 1. Study area and spatial distribution of offshore wind farms.

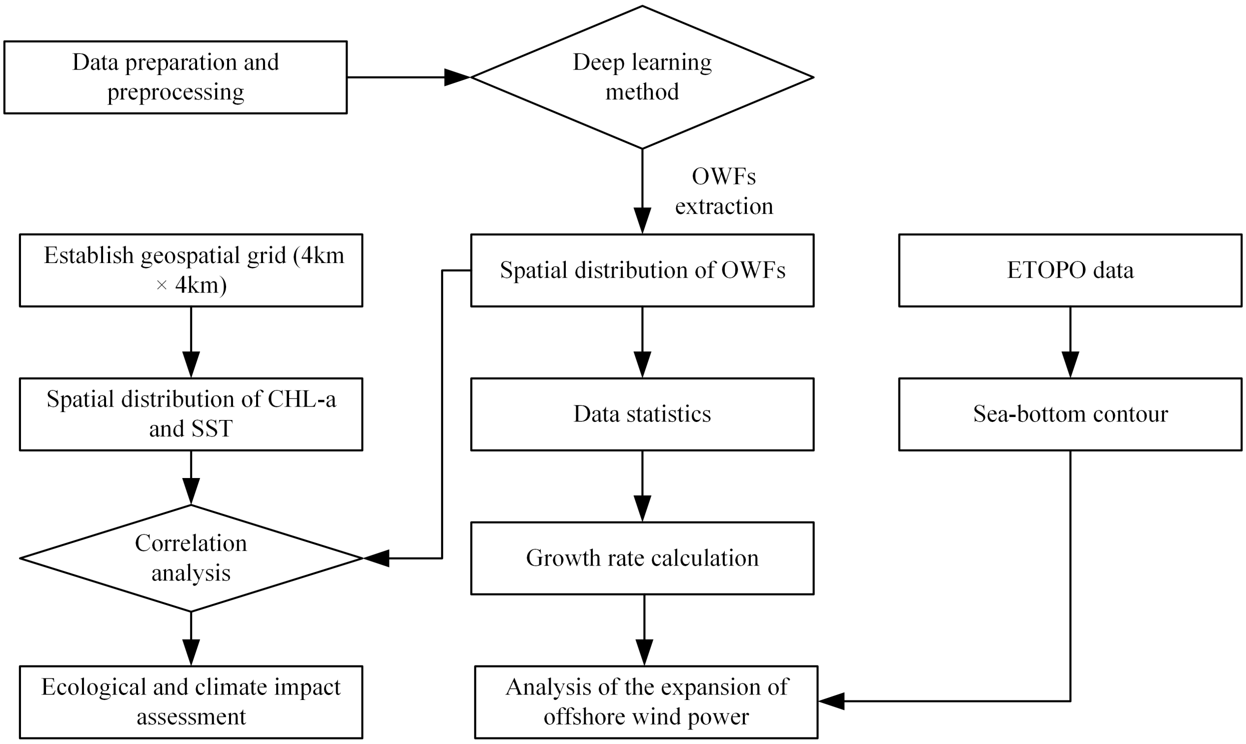

Figure 2. The technique flowcharts.

3. Data and Methods

The research data used in this paper include remote sensing image data, terrain data, chlorophyll-a data and sea surface temperature data. Data attributes are shown in Table 1. The research methods are divided into three parts, one is the extraction method of offshore wind power, the second is the expansion analysis method of offshore wind power, the third is the ecological impact assessment method. The technical flow chart is shown in Figure 2

3.1 Data

The remote sensing image data are GF-2 and GF-7, which are used for offshore wind farm extraction. GF-2 launched in 2014, is China's first wide-width civilian remote sensing satellite with submeter-level resolution, can realize the revisit cycle of no more than 5 days in any part of the world. GF-7 launched in 2019, breaks through submeter-level stereoscopic mapping camera technology and can obtain high-spatial resolution optical stereoscopic observation data and high-precision laser al-

Data name	Date	Spatial resolution	Data sources
GF-2	2016-2022	2 m	Land Satellite Remote Sensing Application Center (MNR)
GF-7	2016-2022	1 m	Land Satellite Remote Sensing Application Center (MNR)
ETOPO	2022	1-arc-minute	National Geophysical Data Center (NGDC)
CHL-a	2022	4000 m	National Satellite Ocean Application Service (NSOAS)
SST	2022	4000 m	National Satellite Ocean Application Service (NSOAS)

Table 1. Data attributes.

timetry data.

The terrain data from ETOPO Global Relief Model, which is used to generate sea-bottom contour to analyze the spatial distribution characteristics of OWFs. The dataset includes land topography data, seafloor topography data. The horizontal datum of the dataset adopts WGS-84 coordinate system and the elevation datum adopts sea level. The data set is available on https://www.ngdc.noaa.gov/mgg/global/.

The ocean water color satellite data, including chlorophyll a concentration data (CHL-a) and sea surface temperature data (SST), are the monitoring result of HY 1C/D satellite. HY 1C/D provides real-time observations of the Northwest Pacific region. The data set is available on https://osdds.nsoas.org.cn/. The spatial distribution of SST in the study area is shown in Figure 3.

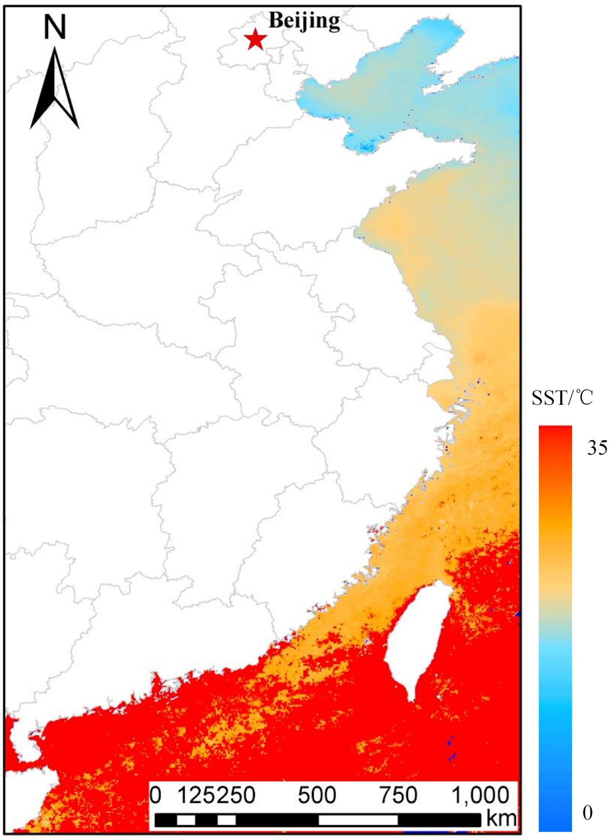

Figure 3. The spatial distribution of SST in the study area.

3.2 OWFs extraction

The remote sensing image data is preprocessed by radiometric calibration, geometric correction and image optimization. Then, the deep learning algorithms are used to achieve offshore wind power extraction. We chose Swin-UNet (Figure 4) as our network to conduct semantic segmentation. Swin-UNet uses

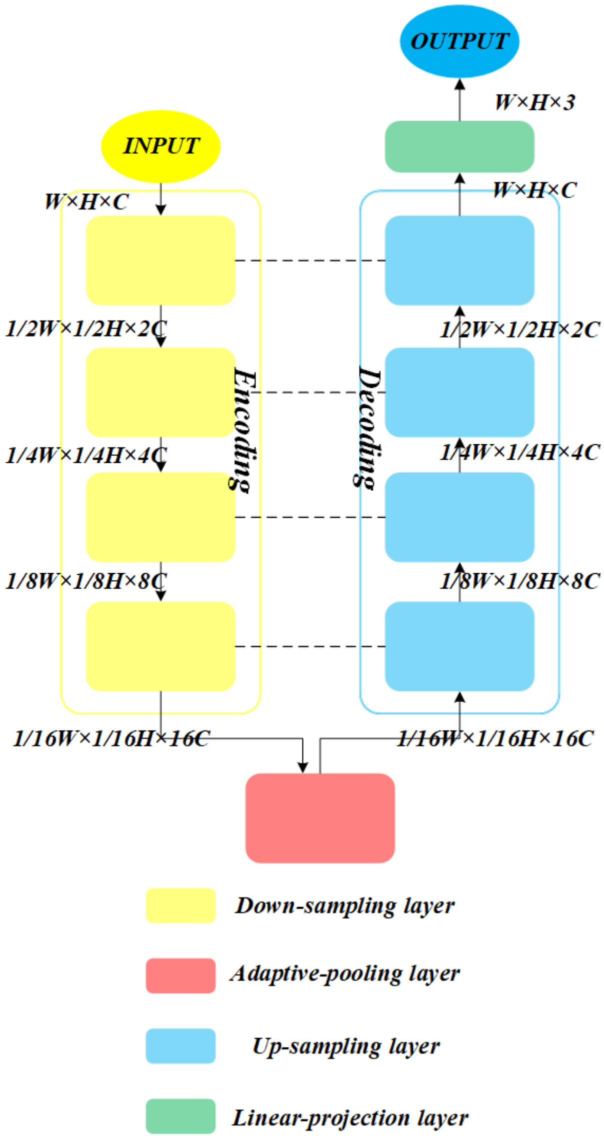

Figure 4. The Swin-UNet.

self-attention module (Figure 5) instead of traditional convolutional layer to encode and decode information from images, thus extracting more specific features on the pixel level.

3.3 Analytical methods for OWF expansion

Based on the distribution data of OWFs from 2016 to 2022 and water depth data, the expansion of offshore wind power is analyzed from the two dimensions of time and space. The rate of expansion of offshore wind power between 2016 and 2022 is expressed as a year-on-year growth rate for each year (Formula 1). In terms of space, the number of offshore wind power facilities in different seawater depth areas is mainly concerned in this study, and the statistical results of different years can

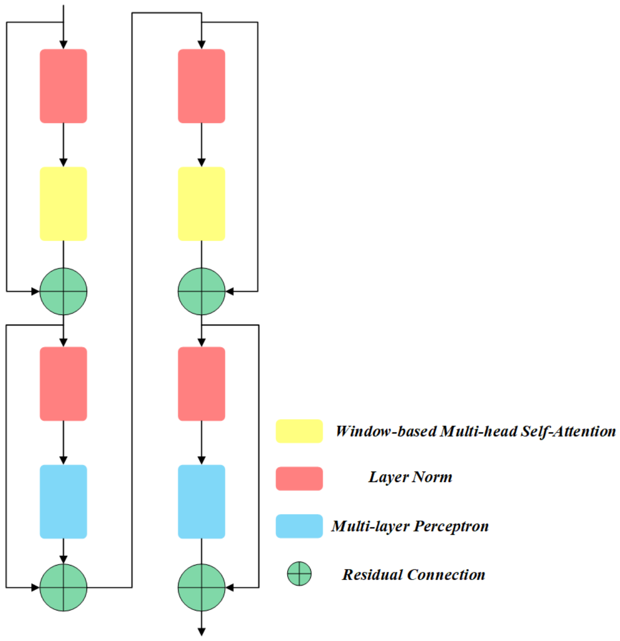

Figure 5. The self-attention module.

be compared to analyze the spatial expansion trend of offshore wind power.

$$GR_i = (N_i - N_{i-1})/N_{i-1} \quad (1)$$

where i = year (2017-2022)
GR = the annual growth rate of offshore wind facilities
N = the number of offshore wind facilities

3.4 Ecological impact assessment method

In this part, the research objects are 10 wind farms from a to j. The ecological impact assessment method is mainly divided into three steps. First, the geospatial grid with size of 4km × 4km is established, and each OWF region has multiple grids (Figure 1 a to j). Then, we take a single grid as the basic statistical unit to count values of CHL-a and SST and the number of wind power facilities in each grid, the more the number, the greater the density of wind power facilities. Finally, taking CHL-a and SST as ecological and climate assessment indicators, and establish the correlation between the density of offshore wind power facilities and the two assessment indicators. According to the correlation analysis results of each offshore wind farm, the impact of offshore wind farms on ecological environment and climate can be assessed.

4. Result analysis

4.1 Analysis of OWFs expansion

Offshore wind power is an important direction for implementing the "dual carbon" goal, continuously optimizing and adjusting the energy structure, and accelerating the green and low-carbon energy transformation. In order to actively promote the construction of offshore wind power infrastructure, China's coastal provinces and regions have issued a series of corresponding policies according to local conditions, and achieved stable and rapid development of offshore wind power. From 2016 to 2022, the number of OWFs in China shows an accelerating growth trend year by year (Figure 6). The annual growth rates are 7.8 %, 12.9%, 14.1%, 14.8%, 25.8%, and 28.0%, respectively; the growth rate in 2021-2022 is significantly higher than that in other years.

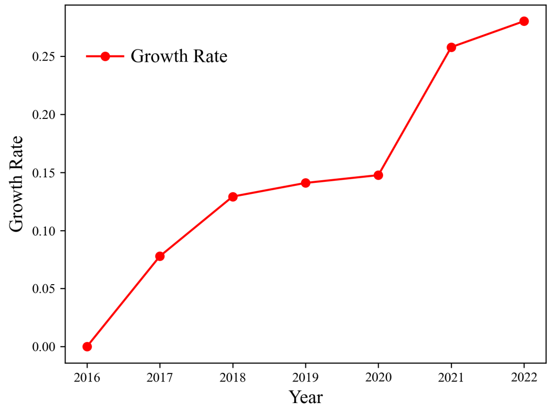

Figure 6. Statistics and growth trend of offshore wind power from 2016 to 2022.

Compared with the near area, the wind resources in the far-reaching area have better conditions, fewer restrictive factors, and can reduce costs and increase efficiency through large-scale development, which has huge development potential in the future. The distribution of OWFs along the coastline is uneven, and the number of coastal wind power in different provinces is quite different. The number of coastal OWFs in Jiangsu Province has increased the most, accounting for 43.3 % of the total national growth, followed by Guangdong and Fujian, accounting for 20.8 % and 11.8 % of the total increasement. The construction of OWFs presents the development trend from offshore to far sea and from shallow sea to deep sea. From 2016 to 2022, the new OWFs are mainly concentrated in sea areas with 5-50 meters water depth, accounting for 84.7 % of the total increase in OWFs. The number of OWFs in the area with a water depth of less than 5 meters has nearly changed.

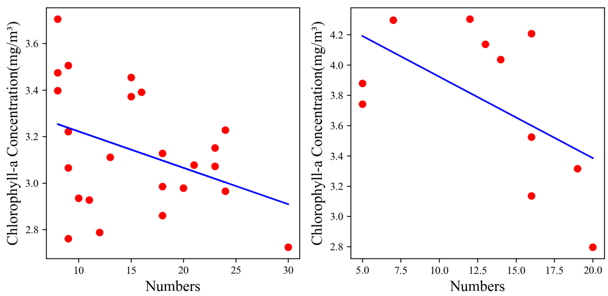

Figure 7. Correlation between offshore wind power distribution density and chlorophyll a concentration (taking two study areas as examples).

4.2 Ecological and climate impact assessment of OWFs

According to the correlation between the wind power facility density and the two indicators of each grid in a wind farm,

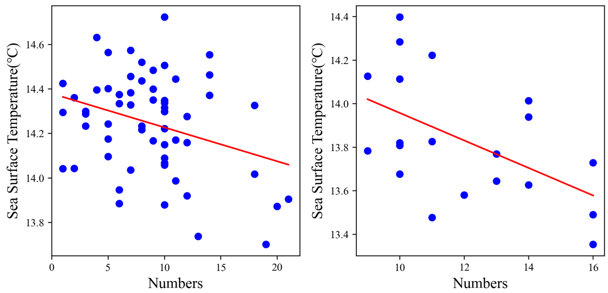

Figure 8. Correlation between offshore wind power distribution density and sea surface temperature (taking two study areas as examples).

the ecological impact of OWF increasing can be evaluated. The higher the number of offshore wind facilities, the lower the value of chlorophyll a. There is a negative correlation between the distribution density of OWFs and the concentration of chlorophyll-a(r=0.51, P<0.05). According to the statistic results, every 10 increases in the number of OWFs in a unit area, the concentration of chlorophyll a (CHL-a) decrease by about 0.29 mg/m^3 on average (Figure 7). The distribution density of OWFs is also negatively correlated with sea surface temperature (SST)(r=0.45, P<0.05). From the statistical results, every 10 increases in the number of OWFs in a unit area, the sea surface temperature decreases by about 0.41 °C on average (Figure 8). The effect of OWFs on ecological environment is related to its distribution density, and the more OWFs, the greater the impact.

5. Conclusion

Based on high-resolution remote sensing image data, the paper used deep learning method to extract the spatial distribution of offshore wind farms from 2016 to 2022. With the extracted data, we analyzed the changes in the scale of offshore wind power construction in China from 2016 to 2022. Then, based on the data and results above, we have made analysis on the temporal and spatial variation characteristics of OWFs. Besides, according to CHL-a data and SST data, we have also studied the impact of OWFs expansion on the marine ecological environment and climateand. The specific results are explored as follows.

(1) The amount of offshore wind power in China has continued to increase from 2016 to 2022. The annual growth rates are 7.8 %, 12.9 %, 14.1 %, 14.8 %, 25.8 %, and 28.0 %.

(2) The distribution of OWF along the coastline is not uniform, most located near Jiangsu, Guangdong and Fujian Province. From 2016 to 2022, the new OWFs are mainly concentrated in sea areas with 5-50 meters water depth, accounting for 84.7 % of the total increase in OWFs.

(3) There is a negative correlation between the distribution density of OWFs and the concentration of chlorophyll-a and SST. The higher the number of offshore wind facilities, the lower the value of chlorophyll a and SST.

To analyze the impact of OWFs industry development on natural resources and ecological environment is of great significance, since it can provide data and theoretical support for efficient utilization of natural resources and effective protection of ecological environment.

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