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Article

Carbon Fiber Composites for Large-Scale Wind Turbine Blades: Applicability Study and Comprehensive Evaluation in China

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Abstract: Wind energy is a type of clean energy that can address global energy shortages and environmental issues. Wind turbine blades are a critical component in capturing wind energy. Carbon fiber composites have been widely recognized for their excellent overall performance in large-scale wind turbine blades. However, in China, the wide application of carbon fiber composites in wind turbine blades still faces many problems and challenges. This paper examines the current state of carbon fiber composites for wind turbine blades and the geographical distribution characteristics of wind resources in China. The economic revenues from increasing the length of wind turbine blades in four typical wind farms, including offshore wind farms, are compared. Using a mathematical model, the energy efficiency of carbon fiber composites in the application of large wind turbine blades is evaluated from the aspects of cost, embedded energy, and carbon footprint. Further, the current relationship between supply and demand for the industrial structure of carbon fiber in China is revealed. The manufacturing technologies for carbon fiber composite wind turbine blades are analyzed, and corresponding countermeasures are proposed. Finally, the incentive policy for applying carbon fiber composites to wind turbine blades is explained, and the development prospects are explored. In this paper, the economics and energy efficiency of the application of carbon fiber composite materials in large wind turbine blades are analyzed and comprehensively evaluated by using mathematical models, which will provide a valuable reference for China's wind turbine blade industry.

Keywords: wind turbine blades; carbon fiber composites; China; energy efficiency; economy efficiency

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1. Introduction

As industrialization continues, human overdependence on and exploitation of non-renewable resources such as coal and oil are growing, causing global impacts on the climate and ecosystems [1]. To address the problems of high carbon dioxide emissions and global warming caused by energy consumption, many countries around the world signed the Paris Climate Agreement in 2016, which aims to keep the global average temperature rise below 2 °C compared to pre-industrialization levels and tries to limit the temperature rise to 1.5 °C [2]. As the largest energy consumer in the world, China pledged at the United Nations General Assembly to reach its carbon peak by 2030 and achieve carbon neutrality by 2060. However, coal and oil are still dominant in China's current energy mix [3], where coal consumption accounted for 55.5% of global coal consumption and 31.8% of global CO_2 emissions in 2020 [4]. In September 2021, due to high coal prices, the shortage of power coal, and the large shutdown capacity of thermal power units in China, a rare severe "Power restriction (Orderly power utilization)" phenomenon occurred in Northeast China. The sluggish energy structure can hardly support the sustainable development of the economy. In addition, China is in the 14th Five-Year Plan stage of promoting a new type of industrialization, economic transformation, and industrial upgrading. Directly limiting greenhouse gas emissions will increase energy costs and negatively affect the economy.

For this reason, the Chinese New Energy Law was enacted in 2020, which deliberately emphasizes the need to promote zero-carbon energy.

Wind energy is a significant new energy source for improving climate and environmental friendliness and enhancing economic competitiveness. Its rational utilization is one of the effective ways to solve energy shortages and global environmental problems in the world today. Therefore, it has become essential for China to develop wind energy construction with a high degree of renewability [5] and promote the rapid development of the wind power industry. Wind turbine blades are the main components required to achieve wind energy capture, and currently, they are mainly made of glass fiber composites or carbon fiber composites [6,7]. Wind turbine blades are usually operated in plateau, mountain, ocean, and other wind-resource-intensive and harsh environments. In recent years, significant accidents involving wind turbine blades have frequently occurred [8,9]. Blade safety issues have become one of the crucial bottlenecks that restrict the development of large-scale blades. Carbon fiber composites have excellent characteristics, such as high strength, low density, and high stiffness [10,11], and have obvious advantages when applied to large-scale blades. With the rapid development of the Chinese wind power industry, the application of carbon fiber composites in large-scale wind turbine blades has become an inevitable trend.

However, the application of carbon fiber composites in wind turbine blades is still facing many problems, mainly in the following aspects. Firstly, due to factors such as cost and manufacturing technology, there is still a certain gap between the proportion of carbon fiber composites in the application of wind turbine blades and international standards. Secondly, China's unique geographical distribution of wind resources increases the demand for lightweight large-scale wind turbine blades. However, the economics and energy efficiency of using carbon fiber composite blades are not clear. Thirdly, China's current industry framework for carbon fiber composites has a supply and demand imbalance, resulting in wind turbine blades made of carbon fiber raw materials mainly relying on imports. Fourthly, the manufacturing technology for carbon fiber composite blades is still in the exploration stage, and the fabrication of crucial structural components is still immature. Fifthly, the excessive use of carbon fiber composite wind turbine blades will increase the cost of recovering waste carbon fiber wind turbine blades in the future [12], which also limits the application proportion of carbon fiber composite materials in wind turbine blades in China. Therefore, it is urgent to conduct a comprehensive economic and energy efficiency assessment of the carbon fiber composite wind turbine blades used in China's wind turbine industry. Therefore, based on China's unique situation, researchers have conducted a lot of research and analysis on China's wind energy resources and the economics and energy efficiency of wind turbines. Juchan et al. [3] revealed the development history of China's wind power industry, the power demand and cost, the regional distribution of wind power, wind turbine manufacturers, and government incentives for the wind power industry through a comprehensive evaluation. However, the economics and energy efficiency of China's wind turbines have not been thoroughly analyzed. Yang et al. [13] constructed a multi-factor learning model under the framework of the Cobb–Douglas function to analyze the unique evolution of the price of wind turbines in China. The influence of various factors on the economics of wind turbines was analyzed from the perspective of the economy. After that, Yang et al. [14] proposed a hybrid multi-criteria decision-making framework, aiming at the diversity of evaluation criteria, the uncertainty of the decision-making environment, and the different risk preferences of decision makers. The best wind turbine can be selected according to different economic and energy efficiency conditions and application conditions. Chong et al. [15] used the two-parameter Weibull distribution function to statistically analyze the typical annual and monthly average wind speed data for Urumqi and Xining in China, and they generated the model of wind turbines used in Urumqi and Xining by using the shape factor k and scale factor c, which were estimated by the maximum likelihood method. The results indicate that different regions in China have different capacities for large, medium and small wind turbines due to the unique distribution characteristics of wind resources. However, the above studies have not fully considered the impact of wind turbine blades made of carbon fiber composite materials on the economics and energy efficiency of wind turbines. Pengfei et al. [16] carried out a finite element analysis of full-size composite blades under different wind speeds in China Jintang Island, Zhoushan Islands. Meanwhile, they introduced the damage model of composites to predict the progressive failure properties and stress distributions of the composite skin for fatigue analysis. Finally, the fatigue life for the carbon fiber wind turbine blade was comparatively evaluated by combining the rainflow counting method, the S–N fatigue curve and the cumulative damage principle. However, the life cycle environmental performance of carbon fiber wind turbine blades was not analyzed. Venkata et al. [17] used polymers reinforced with virgin carbon fiber to make spar caps for wind turbine blades and polymers with glass fiber to make skins for the blade components. They assessed the life cycle environmental performance of the hybrid blades with spar caps based on carbon fiber and the shells and shear webs based on recycled carbon fiber composites. They indicated that the energy and carbon payback times for the carbon fiber turbine blades were found to be 5–13% lower than those of the market incumbents. Although this reflects the advantages of carbon fiber wind turbine blades, they did not analyze the economics and energy efficiency of carbon fiber wind turbine blades in practical applications, which will be carried out in their future work. Meanwhile, their research results may not be applicable to China's unique geographical distribution of wind energy and policy conditions. At present, there is a lack of research literature on the economics and energy efficiency of large carbon fiber composite wind turbine blades and traditional glass fiber wind turbine blades in typical wind farms in different geographical regions of China, based on China's unique wind energy conditions, grid electricity prices, and subsidy policies in different regions, from the aspects of energy, carbon footprint and cost. Therefore, in this paper, statistical analysis and model calculations are employed to evaluate the applicability of carbon fiber composites in Chinese large-scale wind turbine blades, and an analysis system scheme is provided to comprehensively evaluate the economics and energy efficiency of carbon fiber wind turbine blades for China's wind turbine industry. Meanwhile, this paper will help further understand the opportunities, challenges, and solutions for the current application of carbon fiber composites in wind turbine blades in China.

In Section 2, the current situation in China regarding the application of carbon fiber composites for wind turbine blades is analyzed. In Section 3, according to their geographical distribution characteristics, Chinese wind resources are divided into four typical regions, which are introduced. By mathematical modeling and theoretical analysis, the economics and energy efficiency of carbon fiber composites for large-scale wind turbine blades are evaluated in Section 4. In Section 5, the current industrial structure of the supply and demand for carbon fiber in China is analyzed. Section 6 further examines the manufacturing technology problems of using carbon fiber composites for wind turbine blades and proposes corresponding countermeasures. In Section 7, the relevant government policies are presented for the existing issues. Finally, Section 8 gives the conclusions.

2. Application of Carbon Fiber Composites in Large-Scale Wind Turbine Blades

A wind turbine blade is a mixed structure, which mainly includes the skin, spar caps, web, and other structural units. The typical blade cross-sectional structure is shown in Figure 1. Among them, the spar caps and web composed of the main spar area is the primary bearing structure of the entire blade, which is responsible for controlling the blade's overall stiffness (deformation performance), ultimate strength (bearing performance), and shear resistance performance. Moreover, the non-load-bearing or sub-load-bearing structure of the skin shell is mainly used to form the aerodynamic shape of the blade.

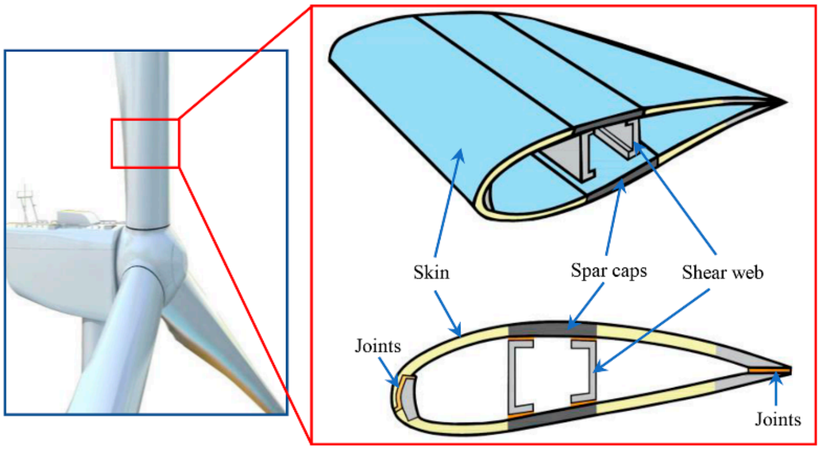

Figure 1. Structural drawing of wind turbine blade.

The development demand for lightweight and large-scale wind turbine blades reveals opportunities for carbon fiber composites in wind turbine blades. Shenzhen Ceres Industry Research Co., Ltd. (Shenzhen, China), points out that, compared with glass fiber composite blades, wind turbine blades made of carbon fiber composites have excellent comprehensive mechanical properties but certain disadvantages, as shown in Table 1. At present, the most crucial part for the application of carbon fiber composites in wind turbine blades is the main spar area. Compared with the main spar made of glass fiber composites, the main spar made of carbon fiber composites can improve the blade stiffness and, at the same time, significantly reduce the mass of the blade. However, considering the higher economic cost of carbon fiber composites, in China, most wind power enterprises still use traditional glass fiber composites to fabricate wind turbine blades. Only a few wind power enterprises use carbon fiber composites in the main spar area, such as Nantong Zhongtai, Zhongfu Lianzhong, and Sinoma Technology. The reason mainly depends on the following two points. On the one hand, the cost of carbon fiber composites compared to glass fiber composites is higher. On the other hand, the technology for manufacturing super-large-scale blades with carbon fiber composites is not mature enough for the manufacturing process and post-installation maintenance.

Table 1. Analysis of advantages and disadvantages of carbon fiber composite blade.

Advantages	Description	Disadvantages	Description
• Improves blade stiffness and fatigue resistance, and reduces blade mass	Compared with glass fiber, the density is about 30% lower, the strength is 40% higher, and the modulus is 3–8 times higher, which improves the blade wear resistance and prolongs the blade life	• Expensive	The cost of carbon fiber is relatively high
• More balanced and smooth energy output	Improves the aerodynamic performance of the blade, reduces the pressure on the tower and axle, and improves the energy output and use efficiency.	• High requirements of manufacturing process	Prepreg molding process requires high, long molding cycle
• Low-wind-speed blades can be manufactured	Making super-large-scale blades and using low-wind-speed blades to reduce power generation cost	• Poor transparency	The transparency of carbon fiber is very low, so it is difficult to detect the inside of the product
• Reduces damage to blades from lightning strikes	It is feasible and can realize lightning protection through grounding	• Strong directivity, poor tangential	It is not easy to make complex surfaces, and the performance of the fiber is reduced after deformation
• Reduce transportation and installation costs	The blade is lightweight, which can save some transportation and installation costs	• High storage requirements	During the transportation, storage, and use of carbon fiber, environmental temperature and humidity requirements are high
• Vibration damping	The resonance between natural frequency and tower can be avoided	• Poor permeability	Poorer permeability than glass fiber, surface treatment required

Moreover, wind turbine blades usually need to work in severe service environments subjected to cold, heat, sand, and seawater erosion [18–22]. In addition to the main spar area of the main load-bearing structure, the need to use carbon fiber composites in non-load-bearing or sub-load-bearing structures is particularly urgent. For example, to improve the fracture strength and load-bearing strength of the material in the blade root part and reduce the dynamic load applied to the bolts, the German company Aerodyn Energiesysteme Gmbh used carbon fiber composites in the blade root [23]. The Danish company LM used carbon fiber composites in the blade tip to reduce the risk of the blade tip striking the tower due to excessive blade polarization [24]. LM used carbon fiber composites in the leading and trailing edge parts of the blade to adjust the intrinsic blade frequency so as to effectively prevent damage from lightning strikes [25]. The U.S. Department of Energy developed wind turbine blades using carbon fiber composites as skins. The results showed that they can reduce the forces and torques acting on the internal support spars and enhance the blade surface strength and corrosion resistance [26]. In China, except for a few companies that have tried to use carbon fiber composites in the main spar area of wind turbine blades, the application of carbon fiber composites in non-bearing or sub-bearing structures of wind turbine blades is relatively rare at present. Thus, in terms of the application of carbon fiber composites in wind turbine blades, China still has a long way to go.

3. Analysis of the Geographical Distribution Characteristics of Wind Resources in China

In China, the average wind energy density is 100 W/m^2, and the total wind energy reserves are about 1.6×10^5 MW, as estimated by China Meteorological Administration. The yearly wind speed is over 3 m/s for almost 4000 h on the southeast coast with surrounding islands; Inner Mongolia; the Gansu corridor; Northeast, Northwest, and North China; and the Qinghai–Tibet Plateau. In some areas of these regions, the annual average wind speed can reach more than 6–7 m/s. This shows that they are promising for the development and utilization of wind energy in China [27]. In addition, China has 20,000 km of coastline and is qualified to build large coastal or offshore wind farms. The distribution of the wind energy density in China is shown in Figure 2. According to the wind energy density and wind speed, the geographical distribution of China's primary wind resources can be divided into four regions: the southeast coast and its islands; Inner Mongolia and northern Gansu; Heilongjiang, eastern Jilin, and the Liaodong Peninsula Sea; and the northern part of the Qinghai–Tibet Plateau: three northern regions and the coast.

China's largest wind energy resource region is along the southeast coast and its islands. The contours of effective wind energy densities greater than or equal to 200 W/m^2 are parallel to the coastline. The wind energy density of coastal islands is above 300 W/m^2, the effective wind speed emergence time percentage reaches 80–90%, and wind speeds of 8 m/s or more occur for approximately 7000–8000 h per year. Wind speeds greater than or equal to 6 m/s also occur for about 4000 h. In addition, offshore wind energy is more uniform and available than onshore wind energy in that region [28]. In Inner Mongolia, northern Gansu, and northern Xinjiang regions, under the control of the westerly wind belt year-round, the wind energy density is mostly 200–300 W/m^2, the effective wind time percentage is about 70%, more than 5000 h per year is spent with a wind speed higher than or equal to 3 m/s, and wind speeds greater than or equal to 6 m/s occur for more than 2000 h. The wind energy density in the three northeastern provinces, namely, Heilongjiang, eastern Jilin, and the coastal area of the Liaodong Peninsula, is above 200 W/m^2. The annual cumulative time of wind speeds greater than or equal to 3 m/s and 6 m/s is 5000–7000 h and 3000 h, respectively. The annual accumulation of wind speeds greater than or equal to 3 m/s is about 4000–5000 h, and the annual accumulation of wind speeds greater than or equal to 6 m/s is more than 3000 h. This means that those four regions are rich in wind energy resources. To date, many wind farms have been built in these four regions, and the development prospects of the wind power industry are extensive.

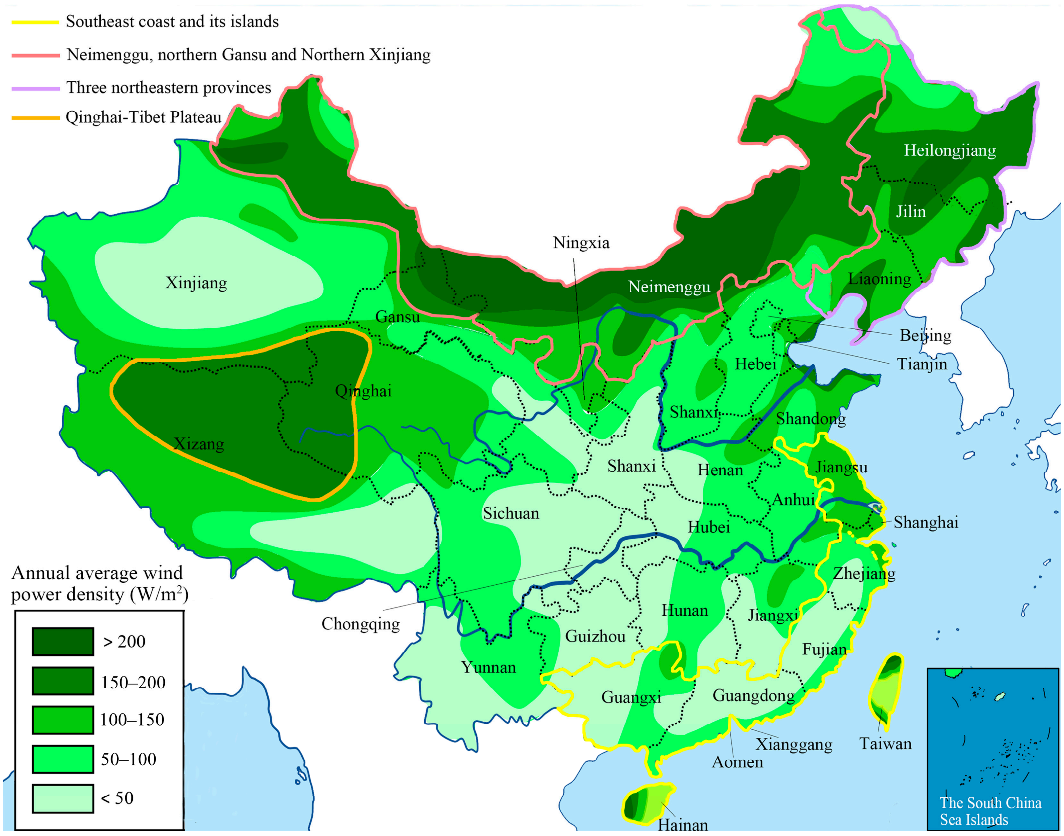

Figure 2. Geographical distribution of wind resources in China.

In the above four typical wind resource accumulation regions, the most representative wind farms are the Nan'ao offshore wind farm in Guangdong Province, the Huitengxile wind farm in Inner Mongolia, the Baicheng wind farm in Jilin Province, and the Mangya wind farm on the Qinghai–Tibet Plateau. In these representative wind farms, the effective wind energy density in one year and the time for which the wind speed exceeds 6 m/s are shown in Figure 3.

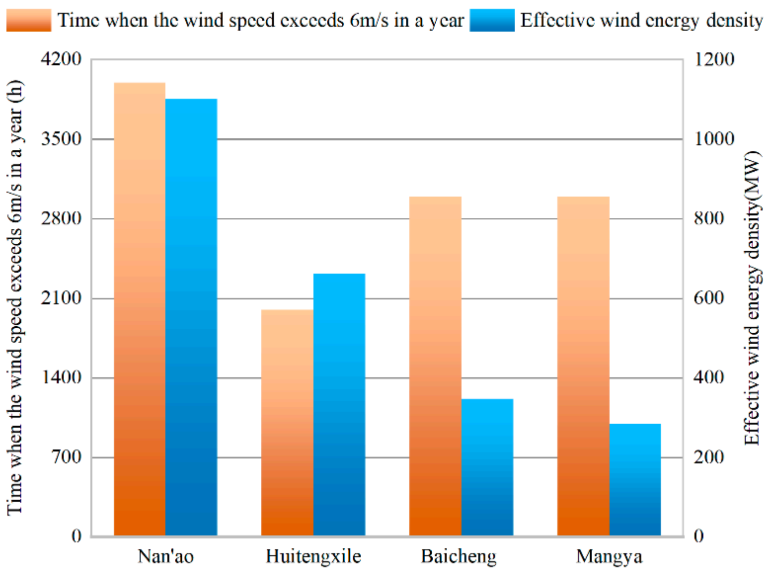

Figure 3. Wind resources of typical wind farms in various regions.

Among them, the Nan'ao wind farm, located at the southwest end of the trumpet of the Taiwan Strait, is particularly rich in wind resources, with wind speeds greater than or equal to 6 m/s for about 4000 h. In the offshore area of this wind farm, approximately 6 MW wind turbines have been installed. The coastal part of this wind farm, with an effective wind energy density of 1101 W/m^2, has wind conditions that are among the best in the world.

Inner Mongolia's Ulanqab City has an effective wind farm area of 6828 km^2 and a technically exploitable capacity of 68,000 MW. For the Huitengxile wind farm in Ulanqab City located on the Inner Mongolia Plateau, approximately 4.5 MW wind turbines have been installed. Wind speeds greater than and equal to 6 m/s occur for more than 2000 h, with an effective wind energy density of 662 W/m^2.

The exploitable wind power area in Baicheng City, Jilin Province, is 6865 km^2, with an installed capacity of 22,800 MW. In this city, 3.3 MW wind turbines have been installed in the Xiangyang wind farm. According to meteorological experts, the total wind power in Baicheng City can generate 207,600 MWh per year, with wind speeds greater than or equal to 6 m/s accumulating for about 3000 h per year, with an effective wind energy density of 348 W/m^2.

The wind energy density of the Qinghai–Tibet Plateau is relatively low, but this still has not hindered the development of Chinese wind power enterprises. In the Mangya wind farm of the Qinghai–Tibet Plateau, wind speeds greater than or equal to 6 m/s accumulate for about 3000 h per year, with an effective wind energy density of 284 W/m^2. Thus, 2.5 MW wind turbines have been installed. At the interface between Jinshan Mountain and the Qinghai–Tibet Plateau, with an average altitude of 3000 m, the 1.5 WM type wind turbine of the Chinese vehicle company Zhuzhou has been grid-connected. These four wind farms are the most representative wind farms in China, although their geographical locations vary greatly and their wind energy conditions are different.

4. Analysis and Evaluation of the Energy Efficiency and Economics of Large-Scale Carbon Fiber Wind Turbine Blades

From the analysis in Section 3, it can be concluded that the unique geographical distribution characteristics of Chinese wind energy resources have led to the accumulation of favorable conditions for the comprehensive development and utilization of wind energy. The rapid growth of the wind power industry has gradually led to the large-scale development of blades. However, the relationship between the wind energy parameters in different geographical distribution regions and the benefits of the large-scale blade is not clear yet. Therefore, changes in the weight, carbon footprint, embodied energy, and cost caused by the application of carbon fibers in wind turbine blades need to be further analyzed. Next, the energy efficiency and economics of the application of carbon fiber composites on wind turbine blades are analyzed and evaluated using a theoretical modeling approach based on the geographical distribution of wind energy resources in China.

4.1. Energy Efficiency Model

4.1.1. Model for Annual Effective Wind Energy Time

The yearly effective wind energy time is a crucial metric for calculating the power generation of a single unit. This research employed the single-parameter Rayleigh distribution curve to calculate statistics on the annual wind speed distribution in various regions and estimate the annual effective wind energy time. The wind frequency function is shown as follows [29,30].

$$f(v) = \frac{\pi}{2}\left(\frac{v}{v_{\mathrm{m}}^2}\right)\exp\left[-\frac{\pi}{4}\left(\frac{v}{v_{\mathrm{m}}}\right)^2\right] \tag{1}$$

where v is the wind speed, and v_{m} is the average wind speed. The effective wind speed of 3–25 m/s is taken in this paper. The effective wind energy time T of one year can be expressed as:

$$T = 365 \times 24\int_3^{25} f(v)\,\mathrm{d}v \tag{2}$$

4.1.2. Model for Single-Unit Power Generation

The wind energy flowing to the output power of the motor end needs to be transformed by the aerodynamic force, transmission chain, and motor. Then, the actual output power of the turbine W can be calculated by Equation (3) [31].

$$W = 1/2\mathrm{C_p}\rho_H {v_r}^3 R^2 \pi \eta_1 \eta_2 \tag{3}$$

where ρ_H is the air density at different altitudes, v_r is the rated wind speed, R is the radius of the wind wheel, and η_1 and η_2 represent the transmission chain efficiency and turbine efficiency, respectively. Under general working conditions, the values of η_1 and η_2 are 0.92 and 0.95, respectively. Based on the study by Hasim [32] et al., the wind turbine power coefficient $\mathrm{C_p}$ determined in this study is 0.45. In addition, the influence of the air density cannot be ignored [33]. The expression for the air density ρ_H in different regions is determined from the gas state equation, as shown in Equation (4).

$$\rho_H = \rho_0 (1 - \alpha H/\mathrm{T_0})^{4.26} \tag{4}$$

where ρ_0 is the air density under the standard state, ρ_0 = 1292 g/m^3. $\mathrm{T_0}$ is the absolute temperature, $\mathrm{T_0}$ = 273 K. α is the air temperature gradient, α = 0.0065 kg/m. Then, the length of the blade at the rated wind speed can be calculated from the above equation.

The annual theoretical power production of a single wind turbine in a certain wind resource region can be expressed as [34]:

$$W_\mathrm{t} = \frac{1}{2}\rho_H AT\mathrm{C_P}\frac{2}{v_\mathrm{m}^2}\left\{\int_{\mathrm{v_i}}^{v_r} v^4 \exp\left[-\frac{\pi}{4}\left(\frac{v}{v_\mathrm{m}}\right)^2\right]\mathrm{d}v + \int_{v_r}^{\mathrm{v_f}} v_\mathrm{r}^3 v \exp\left[-\frac{\pi}{4}\left(\frac{v}{v_\mathrm{m}}\right)^2\right]\mathrm{d}v\right\} \tag{5}$$

where A is the rotor swept area, T is the effective wind energy time, and $\mathrm{v_i}$ and $\mathrm{v_f}$ are the cut-in wind speed and cut-out wind speed, respectively, with $\mathrm{v_i}$ = 3 m/s and $\mathrm{v_f}$ = 25 m/s.

4.2. Economic Evaluation Model

As illustrated by the analysis of the application of carbon fiber composites in the Chinese wind power industry in Section 2, at present, the application of carbon fiber composites in wind turbine blades in China is mainly concentrated in the main spar area of the central bearing part. Therefore, to evaluate the economics of carbon fiber composites in wind turbine blade applications, the wind turbine blade structure is divided into the main spar area and areas other than the main spar. Then, the mass of the main spar area of the blade m_spar, the mass of the other areas m_shell, and the total mass of the blade m_blade can be expressed as [35]:

$$m_\mathrm{spar} = 0.04\left[\left(27.1\pi\rho_H R^3 v_\mathrm{m}^2\right)/\sigma_f\right]^{2/3} R\rho \tag{6}$$

$$m_\mathrm{shell} = 0.04\left[\left(16.5\pi\rho_H R^2 v_\mathrm{m}^2\right)/\Omega\sigma_f\right]^{2/3} R\rho \tag{7}$$

$$m_\mathrm{blade} = m_\mathrm{spar} + m_\mathrm{shell} = (A+B)\rho/\sigma_f^{2/3} \tag{8}$$

where $A = 0.04R\left(26.72\rho_H \pi R^3 v_\mathrm{m}^2\right)^{2/3}$, $B = \left[0.04R\left(16.5\rho_H \pi R^2 v_\mathrm{m}^2\right)^{2/3}\right]/\Omega^{2/3}$, σ_f is the maximum cyclic stress for 10^7 cycles of material, ρ is the density of the material, and Ω is the rotational speed of the blade.

When only carbon fiber composites are used in the entire blade, the ratio of their mass m_CFRP to the mass m_GFRP of a conventional glass fiber composite blade can be expressed as:

$$\frac{m_\mathrm{CFRP}}{m_\mathrm{GFRP}} = \frac{(A+B)\rho_1}{\sigma_{f_1}^{2/3}} \cdot \frac{\sigma_{f_2}^{2/3}}{(A+B)\rho_2} = \frac{212\rho_1}{\sigma_{f_1}^{2/3}} \tag{9}$$

where ρ_1 and ρ_2 are the densities of carbon fiber composites and glass fiber composites, respectively, and σ_{f_1} and σ_{f_2} are the maximum cyclic stresses for 10^7 cycles of carbon fiber composites and glass fiber composites, respectively.

The ratios of the carbon footprint $CO_{2,CFRP}$, embodied energy EE_{CFRP}, and total material cost of the carbon fiber composite blade CO_{CFRP} to those of the glass fiber composite blade are calculated as:

$$\frac{CO_{2,CFRP}}{CO_{2,GFRP}} = \frac{30.37\rho_1 C_{CO_2,1}}{\sigma_{f_1}^{2/3}} \tag{10}$$

$$\frac{EE_{CFRP}}{EE_{GFRP}} = \frac{1.77 \times 10^{-6}\rho_1 C_{EE,1}}{\sigma_{f_1}^{2/3}} \tag{11}$$

$$\frac{CO_{CFRP}}{CO_{GFRP}} = \frac{6.43\rho_1 C_{CO,1}}{\sigma_{f_1}^{2/3}} \tag{12}$$

where $C_{CO_2,1}$, $C_{EE,1}$, and $C_{CO,1}$ denote the carbon footprint per unit mass of carbon fiber composite, the embodied energy per unit mass of carbon fiber composite, and the cost per unit mass of carbon fiber composite, respectively.

When only the main spar of the blade is made of the carbon fiber composite and the rest is made of the glass fiber composite, the ratio of the mass m_{new} of the wind turbine blade to the mass m_{GFRP} of the traditional glass fiber blade is:

$$\frac{m_{new}}{m_{GFRP}} = \frac{m_{spar,1} + m_{shell,2}}{m_{GFRP}} \tag{13}$$

where $m_{spar,1}$ is the mass of carbon fiber composites used in the main spar area of the blade, and $m_{shell,2}$ is the mass of glass fiber composites used in the blade skin.

Then, the ratios of the carbon footprint $CO_{2,new}$, the embodied energy EE_{new}, and the total cost CO_{new} of this type of blade to those of the glass fiber composite blades are:

$$\frac{CO_{2,new}}{CO_{2,GFRP}} = \frac{m_{spar,1}C_{CO_2,1} + m_{shell,2}C_{CO_2,2}}{m_{GFRP}C_{CO_2,2}} \tag{14}$$

$$\frac{EE_{new}}{EE_{GFRP}} = \frac{m_{spar,1}C_{EE,1} + m_{shell,2}C_{EE,2}}{m_{GFRP}C_{EE,2}} \tag{15}$$

$$\frac{CO_{new}}{CO_{GFRP}} = \frac{m_{spar,1}C_{CO,1} + m_{shell,2}C_{CO,2}}{m_{GFRP}C_{CO,2}} \tag{16}$$

In the economic evaluation model, PEEK/IM and epoxy/HS carbon fiber composites [36–38] with excellent performance are taken as the research samples. At present, they are applied in 3D printing, artificial bones, wind turbine blades, and other fields [39–42]. In terms of glass fiber composites, epoxy/E-glass fibers [43] with good overall performance were selected. As indicated in Table 2, material parameters such as density, fatigue strength, carbon footprint per unit, embodied energy per unit, and cost per unit were obtained from the Cambridge Engineering Selector (CES) 2018 database [44].

Table 2. Material properties of different materials.

Materials	Density (kg/m^3)	Fatigue Strength (MPa)	Cost Per Unit Weight (USD/kg)	Carbon Footprint Per Unit Weight (kg/kg)	Embodied Energy Per Unit Weight (MJ/kg)
PEEK/IM carbon fiber	1.55×10^3	1.58×10^3	107.23	50	745
Epoxy/HS carbon fiber	1.55×10^3	1.20×10^3	38.15	46	690
Epoxy/E-glass fiber	1.95×10^3	2.658×10^2	33	6.98	120

4.3. Analysis and Evaluation of Energy Efficiency and Economy

According to the characteristics of the geographical distribution of wind resources in China, typical representative wind farms in different wind resource regions were analyzed according to the energy efficiency and economic models. The wind resource characteristics related to typical wind farms in each region and their corresponding wind turbine parameters are shown in Table 3. In addition, in order to evaluate the change in the profitability of the large-scale blade caused by the adoption of carbon fiber composite, a comparative analysis and evaluation of the energy efficiency and economics were performed by increasing the blade size by 20 m and 40 m based on the baseline blade length calculated by the model.

Table 3. Wind resources, geographical characteristics, and wind turbine parameters of typical wind farms in different wind resource regions.

Regions	Average Wind Speed (m/s)	Average Elevation (m)	Air Density (kg/m^3)	Unit Capacity (MW)	Rotation Rate (rpm)	Blade Length (m)
Guangdong Nan'ao wind farm	10	0	1.29	6	21 16 12	40 60 80
Inner Mongolia Huitengxile wind farm	8.8	1400	1.07	4.5	16 13 11	45 65 85
Jilin Baicheng wind farm	7.8	160	1.27	3.3	19 15 12	42 62 82
Qinghai–Tibet Plateau wind farm	7.5	3000	0.94	1.5	16 13 11	46 66 86

A wind frequency diagram of the four typical representative wind farms based on the results of Equation (1) is shown in Figure 4. It can be seen that the wind speed in the Mangya wind farm of the Qinghai–Tibet Plateau and the Baicheng wind farm in Jilin Province is low most of the time, less than 10 m/s. The wind speeds of the Huitengxile wind farm in Inner Mongolia and the Nan'ao wind farm in Guangdong Province spend more time in one year with a wind speed above 10 m/s, which shows that these two wind farms have more abundant wind resources.

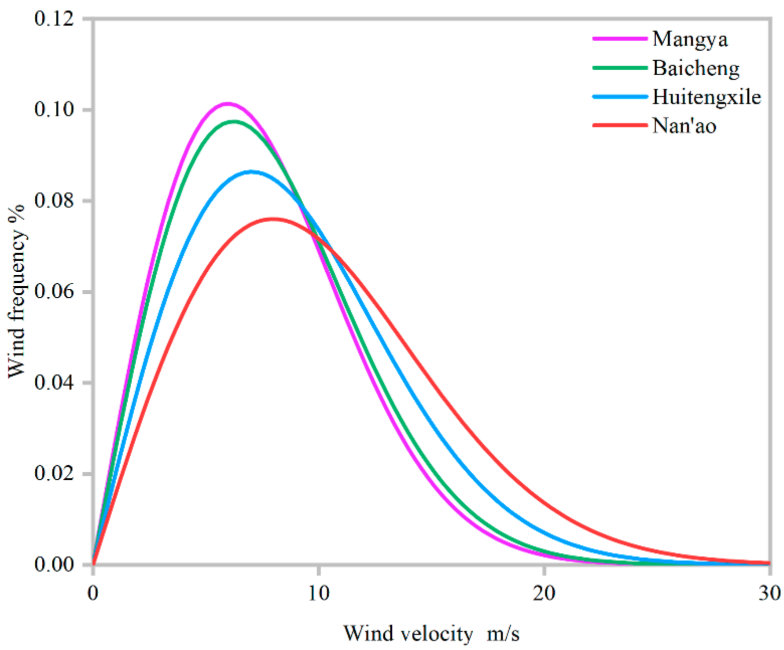

Figure 4. Wind frequency diagram of wind farms in different regions.

According to the wind frequency diagram and Equation (2), we can calculate that the effective wind energy hours of the Mangya wind farm, Baicheng wind farm, Huitengxile wind farm, and Nan'ao wind farm are 7703 h, 7776 h, 7972 h, and 8088 h, respectively. By using Equation (5), the energy efficiency of typical wind farms with different blade lengths in different wind resource regions can be calculated, as shown in Figure 5.

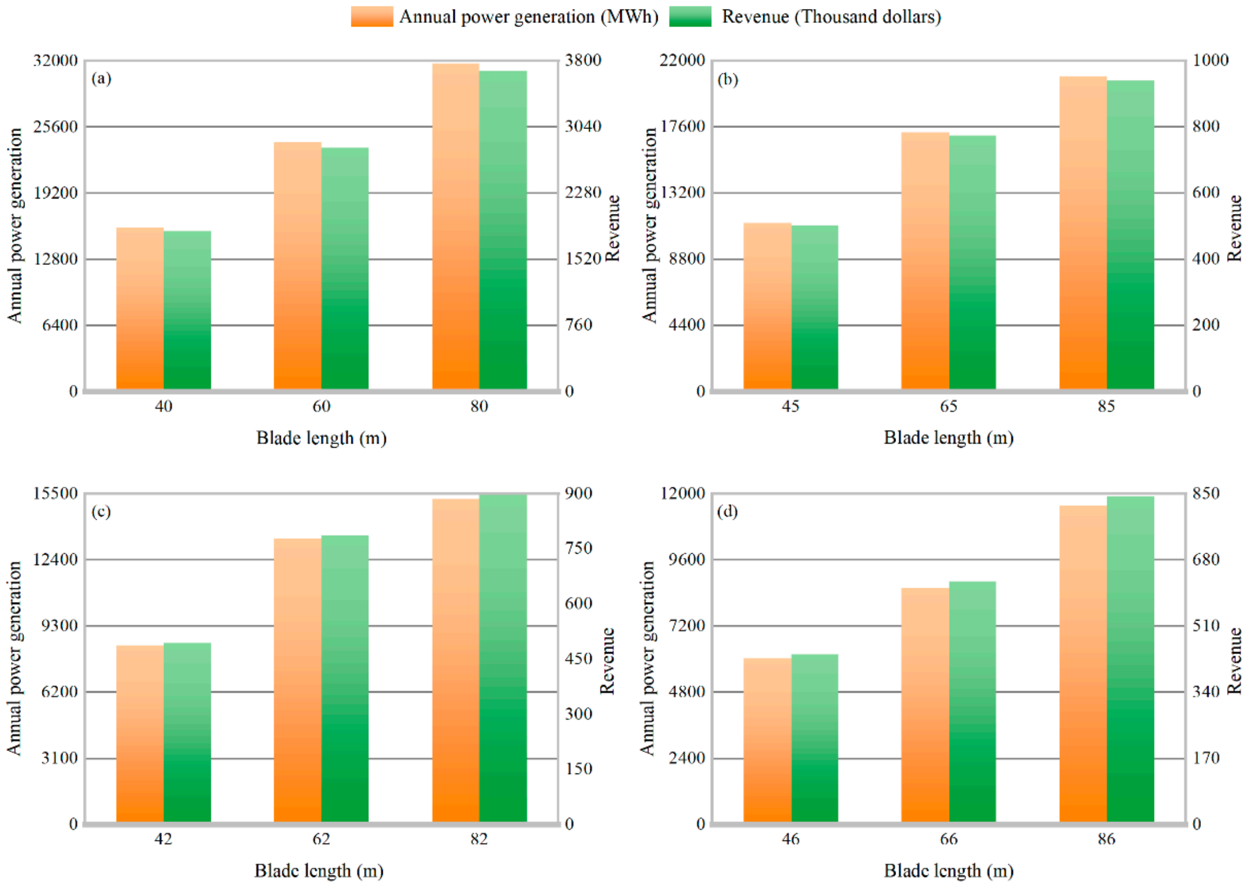

Figure 5. Comparison of energy efficiency after increasing the blade length in different regions: (**a**) Guangdong Nan'ao; (**b**) Nei Monggol Huitengxile; (**c**) Jilin Baicheng; (**d**) Qinghai–Tibet Plateau Mangya. Notes: The feed-in tariffs for Nan'ao, Huiteng Xile, Baicheng, and Qinghai–Tibet Plateau are CNY 0.75 (USD 0.116), CNY 0.29 (USD 0.045), CNY 0.38 (USD 0.059), and CNY 0.47 (USD 0.073), respectively.

Taking the 6 MW wind turbines of the Nan'ao offshore wind farm as an example, if a 40 m long blade is replaced by an 80 m long blade, the annual energy production of each wind turbine will increase by 100%. Moreover, since the base annual energy production is relatively high without increasing the blade length, the annual power generation gain after increasing the blade length is higher. Meanwhile, due to the national support for offshore wind power projects, the feed-in tariff for offshore wind power is very high, and the annual revenue of each wind turbine can increase by USD 1.84 million in theory. In addition, the Nan'ao wind farm is near the coast. Due to the harsh conditions of the sea, high-strength, corrosion-resistant carbon fiber composites in the wind turbine blades can extend their service life. Therefore, it is very suitable to install large-scale carbon fiber composite blades in this region.

For the 4.5 MW wind turbines of the Huitengxile wind farm, the annual power generation increases by 87% after the blade length increases by 40 m, and the basic annual power generation is also relatively high. Due to the low feed-in tariff in this area, the revenue is not exceptionally high, although the power generation is high.

For the Xiangyang wind power farm in Baicheng City of Jilin province, the annual power generation increases by 82% after the blade length increases by 40 m. However, due to the low average wind speed and the influence of the low unit capacity, the basic annual power generation is low. Therefore, after increasing the blade length, the power generation of the first two wind farms is relatively low. However, the feed-in tariffs are different in different wind resource areas. The revenue is not much different even though the power generation is much lower than that of the Huitengxile wind farm.

For the Mangya wind farm on the Qinghai–Tibet Plateau, the single-unit power generation of the wind turbines increases by 89% when the blade length is increased by 40 m. Similarly, due to the influence of low average wind speed, high altitude, and low unit capacity, the annual power generation of a single unit is much lower than that of other wind farms. However, due to the support of feed-in tariffs, the revenue is also considerable. Nevertheless, the altitude in this area is too high, leading to a high cost of transportation and installation for large-scale wind turbine blades and a low generation of power. Therefore, the suitability of large-scale wind turbine blades in the Mangya wind farm may not be ideal.

To sum up, in different regions, it can be found that the longer the wind turbine blades are, the higher the annual energy production at the same rated power, and the more significant the revenue. The longer the blade, the lower the rated wind speed for the same power of the wind turbine. Then, higher power is obtained at low wind speed, increasing the total power generation. However, the longer the blade, the more complex the manufacturing process. Moreover, the larger the turning radius required for transportation, the higher the requirements for road width and marine transport vessels, increasing transportation costs. In addition, with the increase in blade length, the mass of glass fiber blades will increase significantly. Therefore, using carbon fiber composites for manufacturing large-scale wind turbine blades to reduce their mass and increase their strength and service life has crucial economic significance and application value.

At present, the trade-off between economics and energy efficiency in manufacturing large wind turbine blades with carbon fiber composites in China is not clear enough. Therefore, relatively few enterprises use carbon fiber composites to make large wind power blades in China. Next, taking the four typical wind farms in different regions of China as examples, the economic aspect is analyzed in terms of the blade scale and material selection. The comparison results of economics and energy efficiency calculated and plotted using Equation (13) to Equation (16) are shown in Figure 6.

When the main spar of the blade is made of epoxy/HS and the rest is made of glass fiber composites, the cost of the blade is the highest, which is about 80% of the traditional glass fiber blade. However, the carbon footprint and embodied energy are the lowest, and the mass is reduced to about 35% of the traditional glass fiber blade. When the main spar is partially made of PEEK/IM carbon fiber composites and the rest is made of glass fiber composites, the blade has the highest mass, but the cost, carbon footprint, and embodied performance are relatively low. Compared with the traditional pure glass fiber composite blade, the mass and cost are reduced by about 60% and 20%, respectively. However, with the increase in blade length, the proportion of this reduction becomes less and less. For example, when the blade increased by 40 m, the proportions of both mass and cost reductions are only decreased by 3%. When the main spar uses carbon fiber composites and the rest uses glass fiber composites, the carbon footprint and embodied energy are increased by 60–80% compared with the traditional pure glass fiber composite blade. However, similarly, with the increase in blade length, the proportion of this increase is less and less. For example, when the blade length is increased by 40 m, the proportion of the carbon footprint and embodied energy increase is reduced by 2–5%.

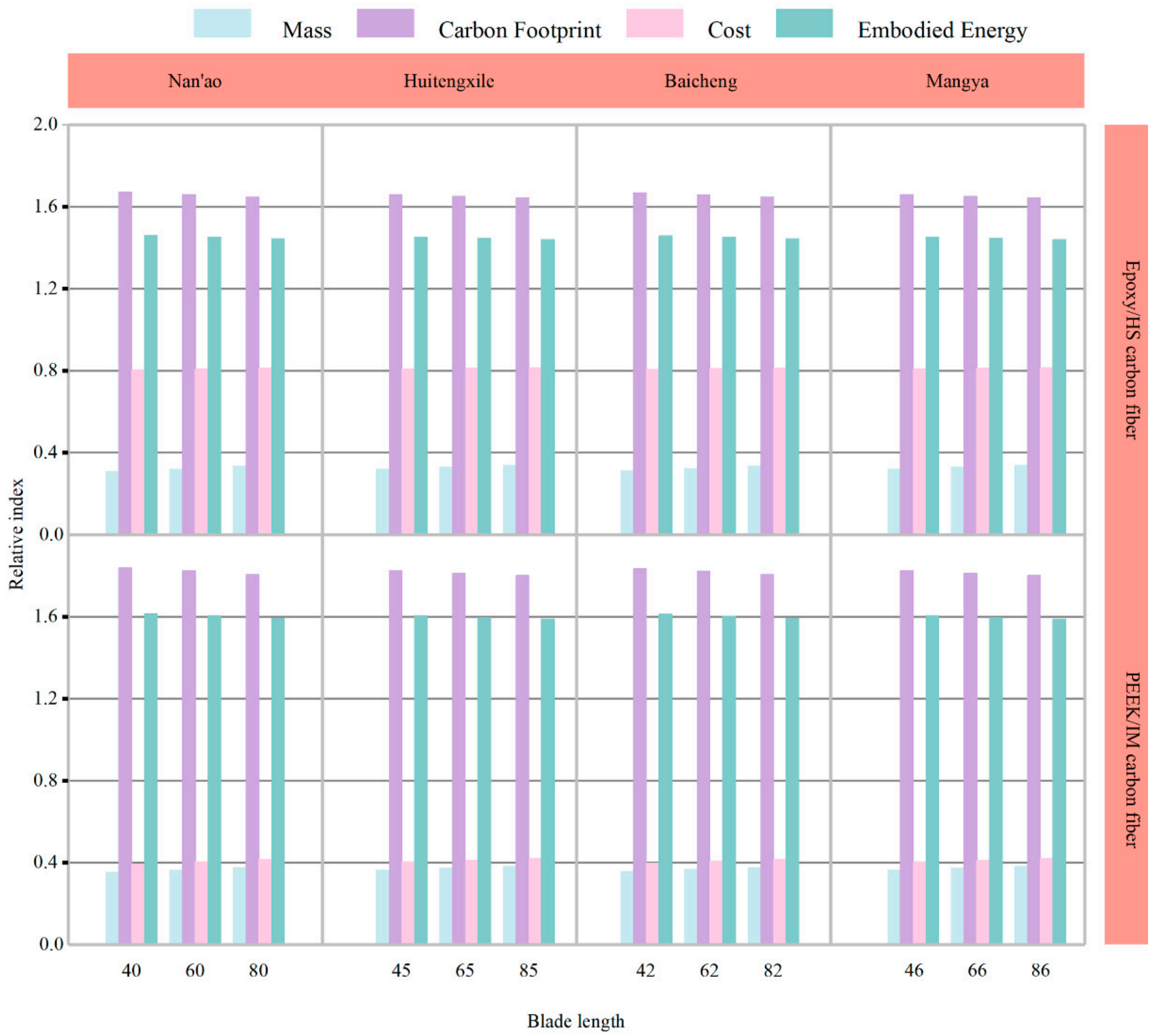

Figure 6. Economic comparison between carbon fiber blade and traditional glass fiber blade. Note: Only the cost of purchasing materials is considered, and the difficult processing, transportation, storage, import tax rate, and other costs of carbon fiber composites are not considered. Only the material mass of the central part of the wind turbine blade is considered.

The blade built entirely of epoxy/HS carbon fiber composites has the lowest cost, costing only 34% of a regular glass fiber blade, but it has the highest carbon footprint and embodied performance, rising by 92% and 67%, respectively. When the whole blade is made of PEEK/IM carbon fiber composites, the mass of the blade is the lowest, which is only about 24% of the traditional pure glass fiber composite blade. However, it has relatively insufficient advantages in reducing cost, carbon footprint, and embodied energy.

To sum up, compared with traditional glass fiber composite wind turbine blades, carbon fiber composite wind turbine blades can significantly reduce the quality and material cost, but the embodied energy and carbon footprint are increased. Although the carbon footprint and embodied energy of a single blade are increased significantly, carbon fiber wind turbine blades with high strength, low weight, and corrosion resistance can bring in higher economic revenue by increasing the service life, prolonging operations, and reducing maintenance. Moreover, although the wind resources vary among different regions, the calculated results are not affected by the environment. This shows that the economics of using carbon fiber composite wind turbine blades in different wind resource areas in China is basically the same. This will provide some reference for the comprehensive promotion of carbon fiber composite wind turbine blades in China.

5. Supply and Demand Structure of Carbon Fibers in China

The application of carbon fiber composites in wind turbine blades has been increasingly emphasized by Chinese companies because of the successful development of the Chinese carbon fiber production industry in recent years. The year 2020 saw strong market growth in the Chinese carbon fiber industry, with a sell-side market for almost all carbon fiber manufacturers and profitable growth for several Chinese carbon fiber companies. As of 14 July 2021, there are 5380 Chinese enterprises whose business scope includes "carbon fiber". Among them, 1032 enterprises producing carbon fibers were registered in 2020, 2.5 times that in 2019. Nevertheless, the number that registered in only half a year in 2021 exceeded the number of registrations in 2020. This shows that the carbon fiber industry in China has experienced explosive growth in the past two years.

Figure 7a shows the operating capacity of carbon fiber raw yarn and carbon fiber in China in 2020, which is 36,150 t, of which 18,450 t is sold, with a sales-to-capacity ratio of 51%. Regarding the design-level-reaching rate, China is crossing the historical stage of a low design-level-reaching rate, and the level is approaching the international level. With China's increasing investment in the field of carbon fibers, the Chinese carbon fiber production share of the world will also continue to increase. The current carbon fiber production capacity in mainland China accounts for 17% of the world's. China's and Taiwan's production capacity accounted for 6% of the world's. The sum of the two has exceeded that of Japan. It can even be reasonably speculated that there will be drastic changes in the global capacity ranking in 3–5 years, and China is expected to become the largest carbon fiber producer in the world.

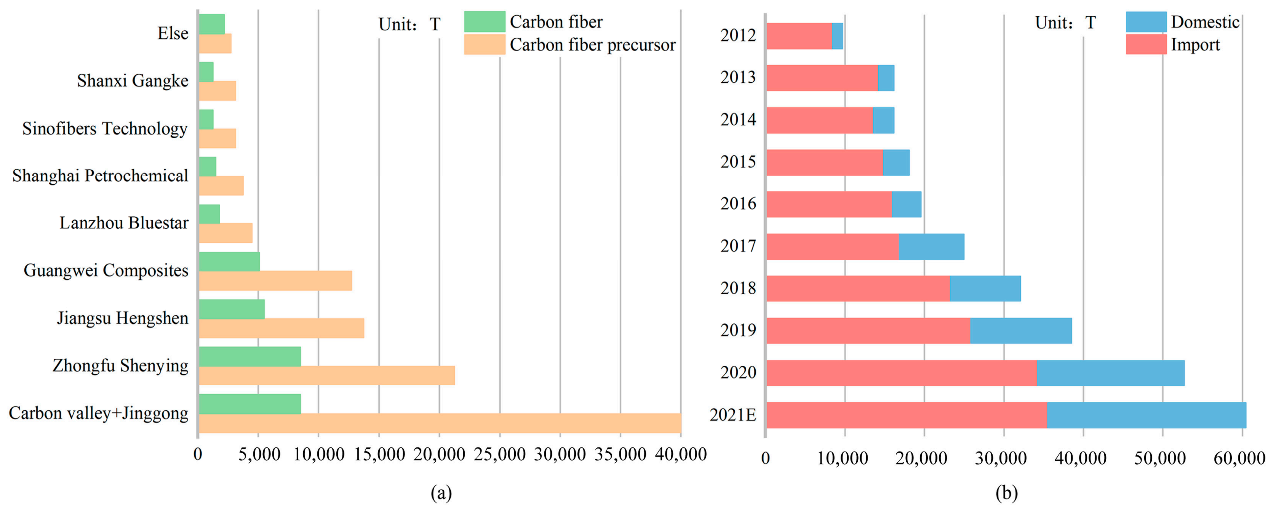

Figure 7. Carbon fiber production and demand in China. (**a**) China's CF precursor and CF operating capacities in 2020 by manufacturer; (**b**) Chinese demand for carbon fibers.

According to Ata Carbon Fiber Tech Guangzhou Co., Ltd. (Guangzhou, China), the total demand for carbon fibers in China in 2020 was 48,851 t, which is an increase of 29% compared to 2019, despite the influence of the COVID-19 epidemic, as shown in Figure 7b. The imports accounted for 62% of the total demand, an increase of 17.5% over 2019. The supply of carbon fibers produced in China is 18450 t, an increase of 53.8% compared with 2019, which demonstrates rapid growth of more than 30% for three consecutive years. It is expected that by 2025, China's domestic production of carbon fibers will exceed imports, which fully shows the vitality of the Chinese carbon fiber industry.

As China's domestic capacity for carbon fiber production grows, more and more Chinese companies are using carbon fiber composites to manufacture wind turbine blades. The 2020 demand for carbon fibers in the Chinese wind turbine blade industry accounts for 40.9% of the total carbon fiber demand, far exceeding other sectors, as shown in

Figure 8. In addition, in China, although the application proportions of carbon fibers in the aerospace and automotive fields are relatively small compared with those in the rest of the world, they have significantly increased in the fields of wind turbine blades and sports leisure. This shows excellent application prospects for carbon fiber composite wind turbine blades in China. Therefore, the development of high-performance and low-cost carbon fiber composites and their application technology is still the focus of relevant research institutions and production enterprises in China.

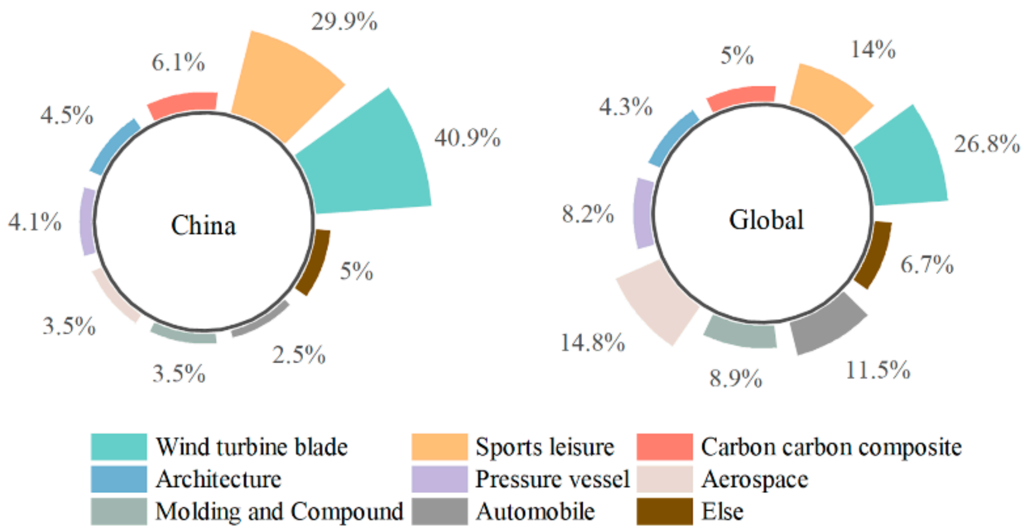

Figure 8. Comparison of carbon fiber applications in China and globally in 2020.

6. Manufacturing Technology for Wind Turbine Blade with Carbon Fiber Composite in China

The development of manufacturing techniques for wind turbine blades in China can be briefly summarized into three stages, as shown in Figure 9.

In the first stage, the traditional glass fiber composite blade is made using a hand lay-up molding process. However, the production efficiency is low, and the product quality and performance stability are hard to control. Moreover, due to the limited performance of glass fibers compared to carbon fibers, the mechanical properties of the product are low and are not suitable for manufacturing large-scale blades. In the second stage, the vacuum bag pressing of prepreg and the vacuum-assisted resin infusion of fabric are gradually being used in most enterprises to manufacture traditional glass fiber composite wind turbine blades, but these two processes are low-efficiency and high-cost. If such materials and methods are used, it is acceptable to only manufacture wind turbine blades longer than 40 m and use carbon fibers instead of traditional glass fibers. At present, the trend in blade size is developing to a large scale, so some enterprises are beginning to try to use small-tow carbon fibers to manufacture the main spar of the blade. Although the performance is much better, the cost is still high. In addition, a high porosity and low content of carbon fibers are often present in the main spar, which seriously limits the application of carbon fibers in wind turbine blades. Until after 2015, Vestas of Denmark successfully applied the pultrusion process to the main spar of carbon fiber composite wind turbine blades, making the use of carbon fiber composite wind turbine blades possible.

At present, China still lags behind the world in terms of the manufacturing technology for carbon fiber composite wind turbine blades. However, China is learning from the experience of Vestas and independently developing new technologies for carbon fiber spars according to the performance characteristics of domestic carbon fibers. Additionally, further efforts have been made to improve the manufacturing efficiency and quality of large-scale carbon fiber composite blades. All of these factors can play a key role in promoting the follow-up R&D and application of large-scale, high-strength, and low-cost carbon fiber composite blades.

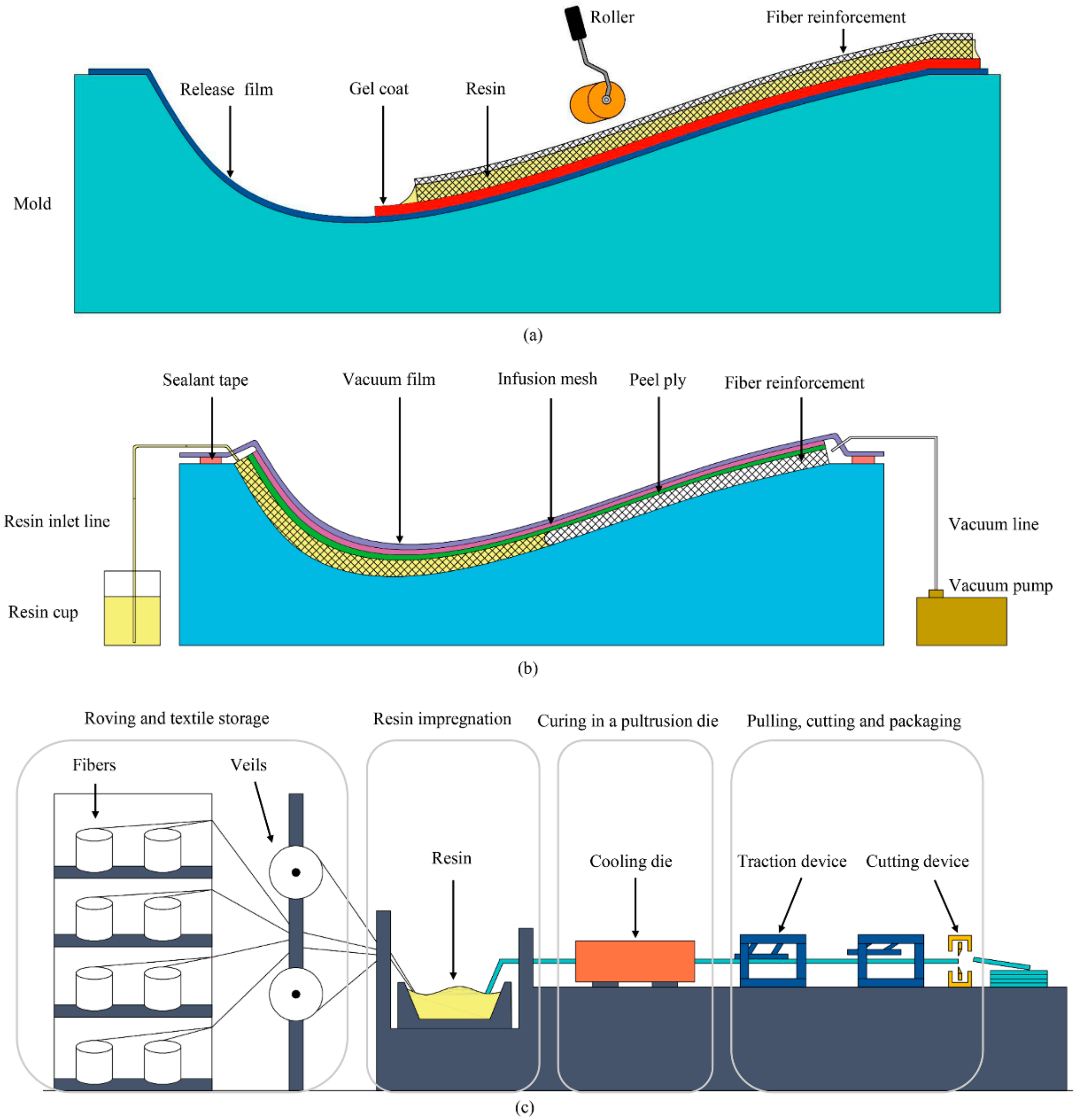

Figure 9. The main stages of manufacturing technology for wind turbine blades. (**a**) Stage 1: hand lay-up; (**b**) Stage 2: vacuum infusion process; (**c**) Stage 3: pultrusion process.

7. Government Incentives and Development Prospects

At the end of 2020, China proposed "carbon peaking" and "carbon-neutral" targets, which require reducing carbon emissions and increasing the proportion of clean energy. However, Chinese urbanization is still in progress, industrialization has not yet been completed, and the energy consumption structure is still dominated by coal and oil. China needs to rapidly achieve emission reduction while promoting development. Therefore, the state has also issued a series of strategic measures accordingly. Under the new energy strategy, the Chinese wind power industry has developed rapidly, accelerated industrial upgrading, and gradually stimulated the demand for the lightweight structure of wind turbine blades. Meanwhile, it stimulates demand for many functions, which has a far-reaching impact on the wind turbine blade industry.

As mentioned above, more and more enterprises in China are beginning to pay attention to the development of carbon fiber wind turbine blades, but Chinese carbon fiber production and application technologies still need to be strengthened. In order to promote the development of the carbon fiber industry, the Chinese government has introduced various incentive policies, as shown in Table 4. In the future, with the support of these policies, the application technologies of carbon fibers in wind turbine blades will continue to develop rapidly. However, some challenges have also emerged: (I) Only the rapid development of the wind power industry is pursued, but its independent innovation ability is not sufficient. Therefore, high-precision equipment and core technologies for producing carbon fiber wind turbine blades need to be imported. (II) With the development of large-scale carbon fiber composite blades, the power generation capacity has steeply increased. However, the lack of grid absorption capacity, unstable wind power generation, and mismatched schedules have caused a mismatch between the national power network and the development of wind power generation, resulting in the phenomenon of wind abandonment. (III) Because the national tariff-setting system is not perfect, the electricity price of wind power generation is low, the initial investment is high, and the return cycle is long, resulting in insufficient funding for many wind power industries. Further, the development pace of China's large-scale carbon fiber composite wind turbine blades has been disturbed. This is consistent with the challenges summarized by Jiahai et al. [45] after summarizing the current situation of China's wind power industry before 2015, indicating that the challenges of China's wind power industry continue to exist. Fortunately, as Jiahai appealed, in response to the above problems, China has further issued corresponding countermeasures, as shown in Figure 10, and the initial results have been achieved.

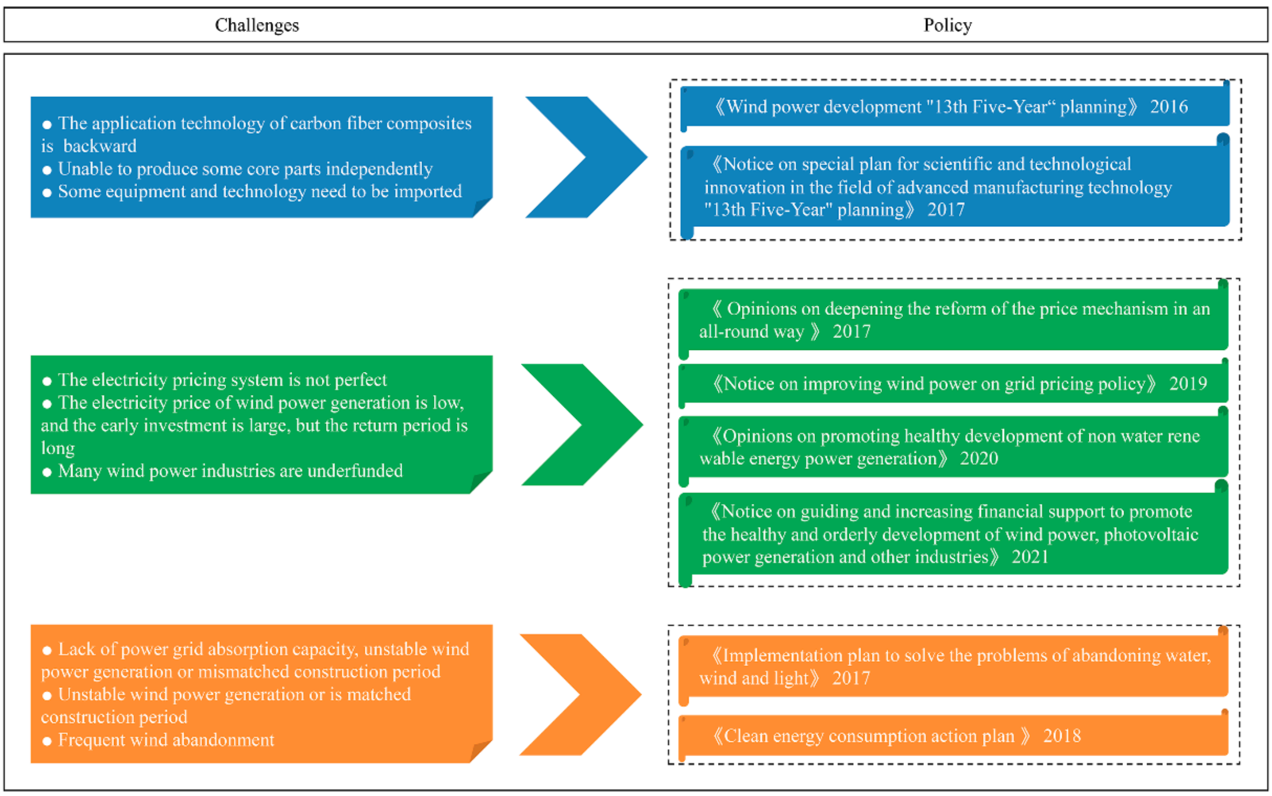

Figure 10. Government policies to address challenges.

Table 4. Government incentives for the development carbon fiber industry.

Incentive Policy	Issuing Authority	Main Influences
The "13th Five-Year" plan for national science and technology innovation	The State Council	It must focus on developing carbon fiber and its composites and superalloys and achieve breakthroughs in the core key technologies for preparation, evaluation, and application.
Petrochemical and chemical industry development plan	Ministry of Industry and Information Technology	Focus on breakthroughs in the technology for the low-cost and large-scale production of high-strength carbon fibers, and accelerate the industrialization of high-strength and medium- and high-modulus carbon fibers.
Development plan of strategic emerging industries in the "13th Five-Year" plan	The State Council	Focus on breakthroughs in domestic low-cost carbon fiber preparation technology and high-end carbon fiber preparation technology, and establish the chain structure of the carbon fiber industry with Chinese characteristics.
Guiding Catalogue of Key Products and Services of Strategic Emerging Industries	National Development and Reform Commission	Take high-performance carbon fibers as an essential product of strategic emerging industry.
Development guide of new material industry	Ministry of industry and information technology	The development direction of essential strategic materials such as high-performance fiber and composite materials is put forward to realize industrialization and scale application.
The "13th Five-Year" plan for science and technology innovation in materials field	Ministry of Science and Technology	It is proposed to work toward breakthroughs in critical standard technology with high-performance fibers, composite materials, and superalloys as the core to enhance advanced structural materials' supportability and international competitiveness.
Industry key generic technology development guide	Ministry of Industry and Information Technology	The standard critical technologies for priority development are put forward, such as "dry jet wet spinning high-performance carbon-fiber technology".
Three-year action plan to enhance the core competitiveness of manufacturing industry	National Development and Reform Commission	It is pointed out that the production and application level of advanced composites should be improved, and the development of high-performance carbon fiber and its application should be emphasized.
New material standard pilot action plan	National Development and Reform Commission	The technical standards for preparing T800 grade and m55j grade and above industrial-grade carbon fibers are proposed to promote the broad application of domestic carbon fibers.
Guide Catalogue for Application Demonstration of the First Batch of Key New Materials	Ministry of Industry and Information Technology	Publish the catalog of critical strategic materials, including fiber materials such as high-performance carbon fibers.
Guidance Catalogue for Industrial Development and Transfer	Ministry of Industry and Information Technology	Shanghai, Jiangsu, and other places accelerate the development of carbon fibers, high-performance composite materials, special functional materials, and other materials.
Special policy of 15 items of carbon fiber	Shanghai Science Committee	Guide and support the high-quality development of the carbon fiber industry.
Pilot work of insurance compensation mechanism for the first batch of key new materials in 2020	Ministry of Industry and Information Technology	For the production of new material products in the guidance catalog for the first application demonstration of vital new materials (2019), the production company can apply for a premium subsidy.

8. Conclusions

In this paper, the application status of carbon fiber composites in wind turbine blades in China is reviewed, the geographical distribution characteristics of wind resources in China are described, and the economics and energy efficiency of carbon fiber composites in large-scale wind turbine blades are evaluated by using mathematical models. The structural relationship between the supply and demand of the carbon fiber industry in China is revealed. Existing issues in the manufacturing technology for carbon fiber composite wind turbine blades are analyzed. The application and development prospects of carbon fiber composites in wind turbine blades are discussed. The specific conclusions are as follows:

- China is rich in wind resources, which is conducive to developing the wind power industry. With the development of large-scale blades, the traditional glass fiber composite blades have difficulty meeting actual needs. Carbon fiber composite wind turbine blades will be an inevitable trend in the future. At present, some Chinese enterprises have begun to use carbon fiber composites in the main spar area of wind turbine blades.
- According to the wind energy density, China's central wind resources are distributed in the following four regions: the southeast coast and its islands; Inner Mongolia and northern Gansu; Heilongjiang, eastern Jilin, and the Liaodong Peninsula Sea; and the northern part of the Qinghai–Tibet Plateau: three northern regions and the coast. Due to the different feed-in tariffs and subsidies given by the state to different regions with wind energy resources, it is found through mathematical model calculations that the economic revenues of using carbon fibers in large wind turbine blades in different regions with wind energy resources are not largely different, which shows that it is feasible to use carbon fiber composites for wind turbine blades in different wind resource regions in China.
- Taking the 6 MW wind turbines of the Nan'ao offshore wind farm as an example, if a 40 m long blade is replaced by an 80 m long blade, the annual energy production of each wind turbine will increase by 100%, in theory. Meanwhile, national support for offshore wind power projects and the feed-in tariff for offshore wind power are very high. In addition, the Nan'ao wind farm is near the coast. Due to the harsh conditions of the sea, high-strength, corrosion-resistant carbon fiber composites in wind turbine blades can extend their service life. Therefore, adopting carbon fiber composite wind turbine blades in offshore wind farms has the best economics and the highest energy efficiency, in theory.
- Compared with traditional glass fiber composite wind turbine blades, carbon fiber composite wind turbine blades can significantly reduce the quality and material costs, but the embodied energy and carbon footprint are increased. In this study, based on the comprehensive analysis of the embodied energy, carbon footprint, cost, and revenue obtained from the mathematical model, it is recommended to use carbon fiber composites to make the main spar and glass fiber composites for the rest of the blade parts in China.
- In China, at present, the carbon fiber industry is experiencing explosive growth. With the Chinese strategy of "carbon peak and carbon neutralization", China is gradually introducing several incentive policies, vigorously developing the construction of zero-carbon energy, and promoting the application of carbon fiber composites in the field of wind turbine blades.
- In terms of manufacturing technology for carbon fiber composite wind turbine blades in China, there are still some challenges, such as high porosity and low fiber content in the main spar area, which seriously limit the application of carbon fibers in wind turbine blades. Accelerating the development of the carbon fiber composite pultrusion process will be the future trend for manufacturing technology for wind turbine blades in China.

In addition, the case study indicates that the computational procedure of the proposed analysis system is sufficiently capable of being implemented with MATLAB 2021a software, which is more user-friendly and convenient for decision makers. The analysis system can be generalized to solve similar issues, benefiting from its universal applicability.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

v	Wind speed (m/s)	α	Air temperature gradient (kg/m)
v_{m}	Average wind speed (m/s)	H	Altitude (m)
v_r	Rated wind speed (m/s)	A	Rotor swept area (m^2)
$\mathrm{v_i}$	Cut-in wind speed (m/s)	Ω	Blade rotational speed (rpm)
$\mathrm{v_f}$	Cut-out wind speed (m/s)	m_{spar}	Spar mass (kg)
T	Effective wind energy time (h)	m_{shell}	Shell mass (kg)
W	Actual turbine output (MW)	m_{blade}	Blade mass (kg)
W_{t}	Theoretical annual output of wind turbine (MW)	m_{CFRP}	Carbon fiber blade mass (kg)
$\mathrm{C_p}$	Power factor of wind turbine	m_{GFRP}	Glass fiber blade mass (kg)
η_1	Transmission chain efficiency	σ_f	Fatigue strength of material (MPa)
η_2	Turbine efficiency	$\mathrm{CO_2}$	Carbon footprint of material (kg)
ρ_0	Air density under standard state (kg/m^3)	EE	Embodied energy of material (MJ)
ρ_H	Air density at altitude H	CO	Cost of materials (kg)
ρ	Density of material (kg/m^3)	$\mathrm{C_{CO_2}}$	Carbon footprint per unit weight (kg/kg)
R	Radius of wind wheel (m)	$\mathrm{C_{EE}}$	Embodied energy per unit weight (MJ/kg)
$\mathrm{T_0}$	Absolute temperature (K)	$\mathrm{C_{CO}}$	Cost per unit weight (USD/kg)

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