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Exploring the Development and Environmental Benefits of Wind Power Technology in Clean Energy Supply

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Abstract:
Wind power is becoming a key renewable energy solution under the dual pressure of global climate change and the energy crisis. Current research is inadequate in terms of technology and ecological synergy mechanism, regional industrial synergy evidence and industry-wide environmental assessment system. This paper analyzes the evolution of wind power technology, energy substitution effect and environmental benefits by integrating statistical data and technical cases, and finds that: carbon fiber blades and other material innovations can increase power generation efficiency by more than 10%, reduce CO_2 by 8 million tons per 10GW installed capacity, account for 10.6% of the national clean energy power generation capacity by 2023, and drive more than 150,000 people's employment and Gross Domestic Product (GDP) growth of 1.8-2.5 percent in Inner Mongolia and other regions. 1.8%-2.5%. The study shows that by promoting the synergistic development of distributed and offshore wind power and scientific planning and site selection, the ecological balance can be realized while guaranteeing the energy supply.

Keywords: Wind power technology; clean energy; environmental benefits; technology iteration; sustainable development.

1. Introduction

Every year, more than 36 billion tons of carbon dioxide are produced by fossil energy combustion, resulting in the Arctic ice cap shrinking at a rate of 13% per decade, and the energy crisis and ecological degradation are intensifying simultaneously, which constitutes a double challenge to the survival of human beings. Wind power, as a clean technology that converts kinetic energy from atmospheric flow into electricity, has become the core path to break the dilemma by the advantage of over 2,000TW・h/year of onshore wind energy and five times the potential of offshore storage on land - with a global installed capacity of 922GW in 2023, it will reduce carbon dioxide emissions by 1.23 billion tons per year. The wind power industry has been a major contributor to the ecological landscape of energy supply [1].

The essence of wind power is an energy conversion process in which the kinetic energy of airflow is captured by wind turbine blades, and the generator is driven to output electricity after the gear box increases the speed. In most cases, as long as the wind speed reaches 3m/s that can start power generation, but also presents a significant scale effect: China's 441.34GW installed capacity in 2023 has achieved 10.6% of the share of power generation, and Ming Yang Intelligence and other companies through carbon fiber blade upgrades, so that stand-alone power generation efficiency to improve more than 10% [2]. More noteworthy is its environmentally friendly attributes, every 10GW installed capacity can replace 3 million tons of standard coal and reduce 8 million tons of carbon emissions per year, this "zero fuel consumption + zero pollutant emissions" characteristics, so that it occupies an irreplaceable strategic position in the "dual carbon" goal [3]. This characteristic of "zero fuel consumption + zero pollutant emission" makes it occupy an irreplaceable strategic position in the "dual carbon" goal [3].

Current research has covered multiple dimensions such as wind power siting, material innovation and ecological interference. Liu Shao-pan coordinates wind farms with regional environmental factors, and clarifies that site selection needs to take into account key factors such as ecological red line and grid access [4]; Zhang Na et al. found that carbon nanofiber paper - glass fiber/epoxy composites can increase the glass transition temperature of the blade from 55°C to 63°C, and the hydrophobic contact angle is increased from 104° to 131°, which significantly improves the performance of the resistance of the impulse corrosion and wear [5]; Zhang Libo et al. investigated the impacts of the wind turbine on birds in Binhai, Yancheng City, Jiangsu Province [6]. Zhang Libo et al. investigated the impact of wind turbines on birds in Binhai, Yancheng, Jiangsu Province, and put forward proposals for continuous monitoring, habitat management and research and development of avoidance technology [6].

Based on this, this paper focuses on the evolution of wind power generation technology and environmental benefits of the coupled relationship, through the analysis of Q460 steel and carbon fiber and other material innovation, 10.6% clean energy ratio of energy substitution effect and "thousands of villages to harness the wind action" and other ecological synergistic paths, to build a "technology - economic - environmental" trinity assessment framework. The evaluation framework of "technology-economy-environment" will provide decision-making reference for the high-quality development of the wind power industry under the goal of "double carbon".

2. The Strategic Significance of Wind Power Technology for Climate Change

Against the background of the intensifying global climate crisis, wind power has become a core strategic means to address climate change with its significant clean energy advantages and environmental benefits. 2023 China's installed wind power capacity will reach 441.34GW, with an annual emission reduction of about 353 million tons of carbon dioxide, and the annual emission reduction of the global 922GW installed capacity will reach 1.23 billion tons, which is equivalent to offsetting 15% of the world's road traffic carbon emissions [1]. Emissions from road transportation [1].

From the perspective of energy structure optimization, China's wind power generation will account for 10.6% of the total low-carbon energy in 2023, and together with hydropower and photovoltaic, the share of coal-fired power generation will be compressed to 56.8% [7]. National wind power grid utilization rate from 96.8% in 2022 to 97.3% in 2023, so that the energy substitution effect of replacing 3 million tons of standard coal per 10GW installed capacity can be fully released [8]. The International Energy Agency predicts that by 2050, wind energy will meet more than 35% of global electricity demand, and can reduce the carbon emission intensity of the energy system by more than 60% [9].

From the perspective of synergistic development of regional economy and energy industry, wind power industry on the regional economic pull effect is significant: Inner Mongolia, Gansu wind power drive employment of 100,000, 50,000 people, to promote the Gross Domestic Product growth, which also called GDP, of 2.5%, 1.8%, the formation of "wind energy development - employment growth - economic upgrading" virtuous cycle [10].

The environmental benefits of wind power are also reflected in the synergistic development of ecology. China's "Thousands of villages to harness the wind action" through distributed development to avoid the single use of land, the Shandong Peninsula offshore wind power base through the "energy production + marine aquaculture" to create a multi-energy complementary paradigm, strictly follows the principle of ecological red line avoidance [11]. In the next ten years, China's wind power installation is expected to add more than 500GW, and the global offshore wind power scale will increase from 11GW in 2023 to 33GW in 2028 (Compound Annual Growth Rate, which is also called CAGR, of 24.8%), which will result in a cumulative emission reduction of more than 10 billion tons of carbon dioxide by 2030 [1].

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3. Iterative Evolution of Wind Power Generation Technology and Innovation Breakthroughs

3.1 Current Status of Wind Power Generation Technology

Domestic wind power generation is developing rapidly, with installed capacity reaching 441.34GW in 2023, accounting for more than 40% of the global share and growing at a rate of 20.7% [8]. Around 2015, the Asia-Pacific region's wind power generation surpassed that of Europe and North America, and the synergistic development of China's "Three Norths" onshore wind farms and the eastern coast's offshore wind power is the core driving force. For example, Guangdong offshore wind power will grow by 25% year-on-year in 2023 [12]. From the 2019 - 2023 installation trend, China's wind power installation increased from 210GW to 441.34GW, and the growth rate rebounded to 20.9% in 2023, highlighting the scale effect.

Global offshore wind power data show that China's 2016 - 2022 new installed capacity growth rate is significantly higher than other Asia-Pacific countries, in contrast to the United Kingdom, the Netherlands, etc., which is directly related to the "14th Five-Year Plan" plan of Shandong Peninsula, Guangdong East and other 10 million kilowatts of base construction. This "onshore first, offshore follow-up" development path, the formation of technology iteration and the installed capacity growth of the dual-wheel drive pattern.

3.2 Material Technology and Iterative Evolution of Innovation

The material technology innovation of wind power generation equipment is centered on "lightweight, high strength and weather resistance", and the differentiation between onshore and offshore applications shows breakthroughs:

In terms of tower material technology, onshore tower adopts Q460 high-strength steel, reduces steel consumption by 15%-20% through conical variable cross-section design, and improves wind strength by more than 30%, and the height of tower in the "Three Norths" region has exceeded 140 meters, with a service life of 20 years [2]; offshore tower adds nickel-chromium alloy, and makes salt spray resistance by multilayer metallurgical composite technology. Offshore tower added nickel-chromium alloy, through the multilayer metallurgical composite technology to extend the life of salt spray resistance to more than 25 years, hollow grouting column structure, than onshore weight reduction of 10%, and compressive strength increased by 50% [2].

Wind turbine, that is, blade material technology, as the core component of wind energy conversion, its material technology in the onshore and offshore scenarios also shows different development paths. Onshore blade adopts carbon fiber - glass fiber composite material, Ming Yang Intelligent MySE series through the main beam reinforcement to increase the blade length from 80 meters to 110 meters, wind swept area expanded by 70%, power generation efficiency increased by 10% [2]; offshore blade application of high-modulus carbon fiber, the weight is reduced by 35%, for example, the weight of the 10MW blade is only 35 tons, the fatigue life of three-dimensional braiding process is increased to 2 times of the traditional materials, the edge of titanium alloy anti-scouring technology, the fatigue life is increased to 2 times of the traditional materials [3]. The three-dimensional weaving process increases the fatigue life of the blade by two times that of the traditional material, and the edge titanium alloy anti-washout strips can resist seawater erosion [13].

4. Environmental Benefits of Wind Power Technology and Sustainable Development Value

The first is the synergistic path of distributed development and offshore wind power. Onshore distributed wind power through the "Thousands of Villages Harnessing the Wind Action" and "PV + " mode, and the full name of PV is photovoltaic, in the countryside, industrial parks to achieve multi-scene synergistic development [11]; offshore wind power relying on Shandong Peninsula and other ten-million-kilowatt bases, combined with the floating technology and marine industry Integration, to promote the development of deep and distant sea parity [14]. Innovative modes such as "photovoltaic corridor" and "offshore energy island" can realize the synergy between energy development and ecological protection [15]. The second is the ecological protection and sustainable development path. Wind power project site selection strictly follows the macro-siting principles, avoiding basic farmland, ecological red line and other sensitive areas, adhering to the principle of avoiding sensitive areas, and balancing the relationship between development and ecology, society and humanity, and investment returns. There is also the strategic significance of addressing climate change. Wind power is an important support for realizing the "double carbon" goal: China's wind power installation is expected to add more than 500GW in the next ten years, and the global offshore wind power will increase from 11GW in 2023 to 33GW in 2028, an increase of 24.8%, which will significantly reduce global carbon emissions [1].

5. Suggestions and Prospects

Wind power is facing multiple challenges in large-scale development: Zhu Yongke and his partners pointed out that there is a lack of research on the assessment of the impact of wind farms on wildlife in China, and the noise of wind turbine operation has triggered complaints from the residents [16]; the problems of weak power grids in remote areas and the cost of offshore deep and distant sea construction technology are not to be ignored.

Technological innovation is from the multi-dimensional breakthrough bottleneck: the Netherlands Robin radar technology in Denmark Vindeby offshore wind farms, to achieve a bird collision rate reduced by 78% [16]; Li Wenhou research and development of noise control devices to effectively reduce the wind turbine operating noise [17]. Offshore wind power technology presents “three” development trend: floating foundation modularity, such as CIMC (China International Marine Containers(Group) Co. Ltd) Raffles semi-submersible platform to shorten the construction cycle of the deep sea and help build China’s largest offshore engineering equipment construction [18], blade material lightweight, such as the application of carbon fiber composite materials so that the weight of offshore blade weight down,; intelligent operation and maintenance management. For example, the use of data-driven methods, offshore wind turbine condition monitoring and fault diagnosis, according to the diagnosis of the type and cause analysis, is put forward based on the state of the wind turbine offshore wind power operation and maintenance strategy [19]. Global Wind Energy Council (GWEC) predicts that the global installed capacity of floating wind power in 2028 will reach 33GW, and China’s “14th Five-Year Plan” new offshore GWEC predicts that the global floating wind power installation will reach 33GW in 2028, and China’s “14th Five-Year Plan” will add 50GW of offshore wind power, with deep and distant sea projects accounting for more than 30% [1].

In the future, it is necessary to build a “policy - technology - ecological” synergistic system: the government to improve the “wind farm bird protection technical specifications”, enterprises to accelerate the research and development of more than 15MW units, scientific research institutes to study the floating foundation stability control and other technologies [15]. As pointed out in the “Global Wind Power Development Outlook 2024”, the integration of technology and ecology will enable wind power to meet 35% of global electricity demand in 2050, becoming the core pillar of the “dual carbon” goal.

6. Conclusion

This paper adopts literature analysis and data modeling methods to systematically analyze the development process and environmental benefits of wind power technology. It is found that: material innovation will increase the efficiency of wind power by more than 10%, and the installed capacity of China will be 441.34GW in 2023, which will account for more than 40% of the global capacity; the annual emission reduction will be 8 million tons of CO_2 for every 10GW, which will account for 10.6% of the national capacity of clean energy generation; more than 150,000 people will be employed in Inner Mongolia and other regions, and the GDP will grow by 1.8%-2.5%; and the synergistic ecological balance will be realized by the distributed wind power and the offshore wind power.

Future research can focus on the construction of an environmental assessment system for the whole industry chain, and the deepening of technology and the ecological synergy mechanism. This study provides data support for the planning of wind power industry under the goal of “double carbon”, and its strategic significance is to reduce the cost of deep and distant sea development through technological innovation, to promote the scale of floating wind power, and to help the green transformation of global energy.

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