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State-of-the-Art and Development Trends of Wind Turbine Technology

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Abstract: The energy produced by wind power is an important renewable resource and is also the focus of China's current efforts to strengthen the global competitiveness of its strategic emerging industries. The development of wind power technology would ensure the long-term success of the industry and a high wind power application ratio. In this paper, wind turbine technology is analyzed at both domestic and international levels to understand its history and current state, and the problems faced by domestic and international markets. Furthermore, some suggestions and prospects for the healthy development of wind turbine technology, promoting structural efficiency, production cost reduction, environmental protection, and resource conservation are also presented.
Keywords: wind power; wind turbine; technology development

1 Introduction

Wind power is a type of renewable energy with high resource potential and mature technologies. Under the current goals to reduce greenhouse gas emissions and mitigate climate change, wind energy has received increasing attention worldwide, and has been developed and utilized on a global scale. During the period from the "11th Five-Year Plan" to the "12th Five-Year Plan," China's wind power industry experienced a decade of rapid development and became the third largest energy source following thermal- and hydropower. According to the statistics published by the Global Wind Energy Council, in 2017, China installed 19.5 GW of wind power capacity, accounting for 35% of the total installed capacity of 188.2 GW. According to the statistics published by the China Electricity Council, in 2017, wind power accounted for 9.2% of China's total installed power generation, and its annual power generation accounted for 4.8% of the country's total power generation [1].

Wind power technology research and development have continued in China for over 40 years, beginning at the same time as that in European countries and the United States. In the beginning, research institutes and universities and colleges researched prototypes and trialed production. During the "9th Five-Year Plan" and "10th Five-Year Plan" period, China's first batch of wind-power machine manufacturing enterprises preliminarily established a suitable overall design for the fixed pitch unit, achieved large-scale production, and took the first step towards industrialized development. As China successively formulated relevant laws and supporting policies to promote the development of renewable energy, such as wind power, since the "11th Five-Year Plan," many domestic and foreign enterprises have heavily invested in China's wind power manufacturing sector by introducing production licenses, establishing joint ventures, conducting independent or joint research, and other means to develop wind turbine products that generate power above the MW level. After a certain period of wind turbine technology introduction and industrial production, domestic wind turbine manufacturers have become increasingly aware of the methods,

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key elements, and potential risks of wind power technology development, and have developed several models with independent intellectual property rights. The single machine capacity is also gradually approaching the leading international level [2].

China's wind power enterprises have established key core technologies through introduction, digestion, and re-innovation, and have made advancements in the development of wind turbines that can adapt to low wind speeds and harsh environments. These enterprises are in a leading position worldwide and have achieved the same pace in the development of large-capacity units as the rest of the world. These achievements not only ensure the sustained and rapid development of China's wind power industry, they also lay a foundation for advancing the industry from great to strong.

To adapt to the widespread low wind speed resources in the central and eastern regions of China, many wind turbine manufacturers have recently implemented high-tower and long-blade programs. In the process of developing technology, they learned from the experience of European manufacturers; however, many new thoughts and methods have been proposed by China's equipment manufacturers to suit local conditions based on domestic resources and industrial support, indicating that China's equipment manufacturers have certain independent innovation capabilities in terms of technical routes.

China's base-level and common technology research in the wind turbine field is relatively insufficient. Most of the software used in wind turbine design and load evaluation are the products of European companies. The design standards and concepts are in accordance with the wind turbine certification rules proposed by DNV.GL and the requirement of the IEC 61400 series standards proposed by the International Electrotechnical Commission (IEC), which do not sufficiently consider China's particular wind energy resources, natural environment, and grid acceptance methods.

The foreign wind power industry is very active in the cross-industry technology integration and transformation of results. It has always led the development of mainstream technologies and still has a leading edge in basic theory, techniques, and material applications. Wind power is a capital and technology-intensive industry that requires equipment to be highly reliable. From a global perspective, owing to the increase in technology and capital thresholds of the wind turbine industry, the industry agglomeration is also improving.

2 Current status of wind turbine technology development

2.1 Current status of large-scale wind turbine machine design development and manufacturing

2.1.1 Development of large-scale wind turbines

Driven by market demand and competition, China's large-scale wind turbine upgrade and internationalization processes have been accelerating. Currently, China's 1.5–4 MW wind turbines have formed a sufficient supply capacity, and some of the unit manufacturers' 5–6 MW wind turbine prototypes have also been used in the field.

Major foreign wind turbine manufacturers have successfully industrialized 4–7 MW wind turbines, and 8–10 MW wind turbine prototypes have been tested. European and American wind turbine-design companies have entered the 10 MW class and completed the machine design stage. Both Vestas and Senvion have announced plans to develop a 10 MW wind turbine with an impeller diameter of approximately 200 m. In 2018, GE announced that they will complete the development of 12 MW offshore wind turbines in three years.

The global development of offshore wind power began in Europe, which also has the largest installed capacity. In 2017, 3 GW of offshore wind power capacity was installed in Europe, which resulted in an increase in the growth of the industry. This indicates that European manufacturers have accumulated abundant experience in design and engineering through years of practice, and they have full confidence that investments will be returned and that the risks of offshore wind power can be controlled.

Currently, 6 MW offshore wind turbines in Europe can be industrialized and installed on a large scale. The 8 MW offshore wind turbines have entered the prototype commissioning phase, and the design of offshore wind turbines with larger capacities has also begun. In terms of the foundation of offshore wind turbines, Europe can design and manufacture a variety of basement forms such as single-pile, multi-piles, gravity piles, and jackets. In the offshore wind power industry, technical, capital, and engineering experience barriers are more significant than those for onshore wind power. Siemens-Gamesa is a significant leader in this field.

A small number of offshore wind farms are operating in China. Owing to the lack of demonstrative experience of offshore wind farms, coordination between the design of wind turbines and offshore wind power projects is insufficient, resulting in large offshore wind power investment costs, lines, and substation design costs that are difficult to reduce; moreover, as the reliability of these units has not been fully verified, the return on investment of offshore wind power has great uncertainty. Therefore, through in-depth customization and research on wind turbine control strategies and blade, tower, and grid-connected characteristics, wind turbines and offshore wind power engineering design can be optimized to prevent the excess and waste created from separately designing each component; therefore, offshore wind power costs will be effectively reduced.

2.1.2 Parts and components supply

China's wind power industry has a production system for parts, including blades, towers, gearboxes, generators, pitch and yaw systems, hubs, and converters. The output of these major components is ranked first worldwide. In addition to supporting domestic manufacturers, some parts and components are also sold to foreign manufacturers. However, domestic high-performance bearings, greases, sensors, and controllers cannot yet fully replace imported parts.

China's wind power industry has accumulated extensive experience in engineering applications. However, there are still some shortcomings in certain aspects of the design principle and optimization method, the application of new materials and new processes, multi-physical field simulation, and full-performance verification tests in the development and quality control of high-performance parts. Further, many weaknesses persist in the research of unit control technologies and correlations between the specific operating performance of complete machines and parts.

In general, China's wind power and component industries are great but not strong, and to different extents, extensive but not refined. Research on basic materials and process technologies is relatively lacking, and there is still a gap between the long-term reliability and consistency of domestic and imported products. Most component manufacturers focus on themselves when considering design development and engineering applications, and need to further strengthen their systematic understanding and cooperation in the industrial chain.

2.1.3 Wind power test platform

Most foreign wind power laboratories cover wind energy resource assessment, wind turbine site testing, transmission chain platform testing, and grid-connected wind power simulation. For example, the National Renewable Energy Laboratory (NREL) has established wind energy resource prediction models at different time scales, a 7-MVA multi-function grid disturbance simulation device, a 5-MW wind turbine drive chain test platform, and other research platforms that internationally lead the testing and development of wind/photovoltaic power equipment and parts; the research by the Danish National Renewable Energy Laboratory (DTU/RISØ) in the field of wind energy includes wind energy resource and microsite assessment, wind power forecasting, wind power grid connection and control, offshore wind power, aerodynamics research and design, structural function and reliability design, remote sensing and testing, boundary layer meteorology and turbulence, and materials.

Currently, only some wind power enterprises in China have their own power test platforms. Moreover, their test functions are relatively simple, and they are not well known or independent. Most manufacturers conduct research experiments based on their own experience, understanding, and product development focus, and public relations are insufficient.

In 2010, China established the National Wind Power Technology Testing and Research Center in Zhangbei, and conducted a series of on-site wind power equipment performance and grid adaptability tests at public test sites, providing China with sufficient support for improving the capability of industrial technology and accelerating development.

The most suitable area for the development of offshore wind power in China is the southeast coast, which experiences typhoons, salt spray, high temperatures, dampness, and other harsh climate characteristics. Currently, China has no wind power application environments or systematic professional testing capabilities to deal with these wind power application environments; hence the construction of relevant testing capabilities must be strengthened. In Europe and the United States, several testing and research activities have assessed the impacts of offshore wind farms on hydrology, power grids, meteorology, and biology during construction and operation, and specific test equipment has been developed.

2.2 Current development status of digital wind power technology

With the rapid development in the capacity of the wind power generation market and the equipment industry, the reliability, operational efficiency, and working life of wind turbines have begun to receive attention from experts and scholars. In response to these challenges, digital wind power technologies have been developed through the in-depth research and exploration of intelligent monitoring, operation and maintenance, fault diagnosis, and early warning systems for wind power.

2.2.1 Intelligent wind power monitoring

Owing to the different electronic technologies, control technologies, wind turbine sizes, and software versions, the control methods of wind turbines produced by the same manufacturer may differ, and different operating parameters and control instructions are required, which create great obstacles for the unified control and production management of a wind farm; hence, it is difficult to interconnect and expand these systems.

To enable interconnectivity, interoperability, and scalability in wind farms, the IEC drafted standard IEC 61400-25, which defines the communication principle and information exchange model for building a wind farm monitoring system. It is an extension of the power system automation communication protocol of standard IEC 61850 for wind power generation. China has also transformed and implemented a national standard for IEC 61400-25, which enabled the management of monitoring wind farms.

2.2.2 Intelligent wind power operation and maintenance

China's wind power equipment mostly operates under harsh natural conditions. The demand for intelligent operation and maintenance is particularly urgent. Considering influencing factors, such as the reliability, maintainability, and cost of the equipment, there is a need to establish a reasonable arrangement for regular checking, repair, and maintenance to reduce the number of duty staff, shorten the part distribution time, and improve operational reliability.

Foreign countries implemented intelligent operation and maintenance management systems for wind farms earlier than China, and the level of practicality is high. In addition to the traditional functions of data collection, analysis, and presentation, the advanced control functions of wind farm optimization, operational data analysis, supply chain service, and information flow management, which initially embodied the concept of intelligent operation and maintenance of wind farms, have been integrated into GH-SCADA, RISO-CleverFarm, and other tools as carriers of wind farm control systems.

There is wide disparity in the level of refinement and informatization of intelligent operation and maintenance between China and the international community. There are significant differences between the operational conditions, service equipment, and safety requirements of offshore and onshore wind farms. The systematic approach of European manufacturers to the operation and maintenance of offshore wind farms is based on years of experience. However, the operation and maintenance methods and concepts for offshore wind farms in China mainly draw from the experience of onshore wind farms, and an operation and maintenance management system that is truly applicable to offshore wind farms is yet to be developed.

2.2.3 Intelligent wind turbine fault diagnosis

In China, a large number of wind turbines are out of warranty in succession. The availability of wind turbines has decreased, the performance of their transmission systems and blades has declined, and the downtime caused by faults has become more serious. Some domestic scientific research institutions and machine manufacturers have gradually increased their focus on health diagnosis technology for wind turbines and have conducted preliminary research based on advanced foreign experience. Some state monitoring products have also been developed and implemented in wind farms in batches.

Some developed countries that use wind energy, such as Denmark, Germany, and Spain, have a long-term symbiotic relationship and close cooperation among the wind power component and complete machine industrial chains, and conduct wind turbine operation status evaluations and life cycle assessments using a large amount of in situ operational data. Wind energy resources, power planning, farm assessment, turbine equipment operation status and test results, wind farm operation and maintenance, and wind farm performance evaluation are considered when evaluating wind turbine statuses, diagnosing faults, and assessing the cost of operation.

With the development of big data technologies, all wind turbine manufacturers have established big data centers and researched methods of monitoring conditions and pre-diagnosis. However, the product analysis and diagnosis of domestic wind turbine fault diagnosis technologies are relatively weak, and the main problem is that China's understanding of the operating mechanisms and failure processes of complete machines and parts is insufficient. Current technologies focus on determining trends and qualitative analysis with a lack of quantitative analysis, and there is currently no complete evaluation system or accurate judgment and warning methods for faults.

2.3 Current development status of grid-friendly technology

Alongside the increasing proportion of wind power, China has proposed new requirements for the grid-connected performance of wind turbines, including low voltage ride-through, high voltage ride-through, inertia responses, and primary frequency modulation. Currently, low voltage ride through is a mandatory requirement for wind power equipment in China. The requirements for high voltage ride-through, inertia response, and primary frequency modulation capabilities are under further study; however, no clear technical indicators and test methods have been proposed. Each country has proposed targeted wind power equipment access standards according to their own power systems. In some countries, the requirements for high and low voltage ride-through and the primary frequency performance of wind power are very clear.

Foreign equipment manufacturers have conducted in-depth research and development on the dynamic characteristics, safety limits, interaction stabilities, wind turbine and farm verification models, and the evaluation of the quality of wind turbines according to their fault ride-through, and have conducted corresponding tests. However, domestic manufacturers are mostly focused on achieving functional wind power systems, and the in-depth exploration and optimization of technologies still need to be strengthened.

As China's wind power scale has grown rapidly in recent years, and considerable practical experience and achievements in terms of large-scale grid connection and the transmission and operation of wind power has been gained, the IEC established the new TC8 SC8A "Large-Capacity Renewable Energy Access to The Power Grid" working group, and the secretarial department of the TC8 SC8B "Distributed Energy Power System" working group in China. This has allowed Chinese technical experts to participate in the formulation of international standards and more extensive technical exchanges, which have greatly improved the position of China's wind turbine industry in the field of power grid access technologies.

2.4 Current development status of wind power new concept technology

In addition to traditional technologies, new wind power concepts have also rapidly developed. To meet the needs of future large-capacity offshore wind turbines, the United States signed an agreement with the National Renewable Energy Laboratory (NREL), American Superconductor Corporation, and the TECO Westinghouse Motor Co., Ltd. in 2009 to jointly develop superconducting generators to support large-capacity wind power. Many European manufacturers have also entered this field. The United States General Electric Company and American Superconductor corporation, Germany's Siemens AG, and Japan's Kawasaki Heavy Industries, Ltd. have all trialed the production and testing of megawatt superconducting generators. The CSIC 712 Research Institute has conducted such prototype development in China [3].

A high-temperature superconducting machine involves the multi-disciplinary, advanced application of new materials, methods, and techniques. It is technically difficult, and domestic research in high-temperature superconducting machines has started later than that in other countries. The research and development costs are small, and the depth and breadth of research and development insufficient. Between China and the United States and Germany, there is a notable disparity in basic research, technical level, and technical methods for these machines.

Near the ground, wind energy has shear characteristics owing to the surface roughness, i.e., the higher the altitude, the greater the average wind speed. Therefore, many years ago, the utilization of high-altitude wind energy resources received attention from scholars both in China and abroad [4]. High-altitude wind power is still in the exploration stage in China. Some small power units are under trial operation; however, there are no commercial cases.

Foreign companies have developed novel solutions towards harvesting high-altitude wind energy. Google acquired Silicon Valley's high-altitude wind power entrepreneurial company (Makani power), and the Massachusetts Institute of Technology has invested in Altaeros Energies, Inc. both of which have designed and manufactured a prototype site test [5]. In the field of high-altitude wind power, foreign manufacturers have a great technical research and development starting point, a solid theoretical foundation, a large number of new materials and sensors that are currently in practice, and a mobile, flyable, and recyclable route for equipment design. The economic efficiency of their projects is high, and they are superior to those being conducted by domestic manufacturers.

3 Technology development trends and needs

China will continue to implement land-based, large-scale base construction, decentralized onshore grid-connected development, and offshore wind power base construction, and actively promote the export of complete equipment and parts in combination with the national strategy for transforming and upgrading China's manufacturing sector. To fully utilize wind energy resources and reduce electricity costs, the development of wind turbines is continuing towards large-scale, intelligent, and digital machines, and specific technological breakthroughs will occur through informatization, clustering, and multidisciplinary cross-integration.

3.1 Development trends and needs for design and manufacturing of complete large-scale wind turbine machine

3.1.1 Large-scale wind turbine development

With the continuous increase in the single unit capacity of wind turbines and development of wind power in China and through the integration of advanced sensing and big data analysis technologies, future intelligent wind power equipment research will lean towards the use of intelligent control technologies to analyze the operating status and working conditions of wind turbines and allow real-time adjustments to operation parameters. This would result in the efficient and highly reliable operation of wind power equipment.

The main technical requirements of complete large-scale wind turbines include: integrated design optimization and lightweight design technologies; integrated optimization technologies for blades, loads, and advanced sensing control; and intelligent electrical-control system diagnosis, maintenance-free self-recovery technologies, and sustainable manufacturing technologies for wind turbines and key components.

The composition of China's seabed will result in higher engineering costs for China's offshore wind turbines than those in Europe, and the summer typhoon that occurs in China's seas poses a serious challenge to offshore wind turbine development. Therefore, China's offshore wind power market has a greater demand for equipment with a large capacity and high reliability.

The technical requirements of offshore wind turbines mainly include: key design, construction, transportation, and hoisting technologies that are applicable to offshore and high-sea wind farms in China; accurate modeling, and simulation technologies that are suitable for China's sea conditions and offshore wind energy resources; 10-MW and above design technologies for offshore wind turbines, including wind turbines, towers, basic integrated design technologies, and design optimization techniques that consider ultimate and fatigue loads, and machine reliability; design, manufacturing, and testing technologies for high-reliability transmission, key components, and cooling technologies for large-scale wind turbines; offshore wind turbines and their key components, such as bearings and generators, with independent intellectual property rights; impacts on the internal mechanical and electronic control components and external structural corrosion from the harsh marine environment; and an intelligent adaptive system for wind turbines experiencing typhoons, salt spray, high temperatures, and high-humidity marine environments.

3.1.2 Parts and components supply

As large-scale wind turbines are enlarging, the importance of structural problems is increasing. Some new technical solutions, such as segmented blades, split-steel flexible towers, small low-cost auxiliary control laser radars, and highly biodegradable oil products that are used in offshore units are not fully mastered in China.

Increasing the size and flexibility of blades can cause new problems, such as reductions in the first-order torsion frequency aeroelastic divergence and flutter stability boundary of the blade, and they may even impede the normal operation of the wind turbine. Therefore, conducting aeroelastic stability analysis for the turbine blades will be an essential part of future large-scale blade structure design, and the aeroelastic stability of the blade must be improved through enhancing its structural design [6].

3.1.3 Wind power test platform

Domestic manufacturers normally conduct product performance tests to meet product certification and market access requirements. The test platforms that have been developed by wind turbine and component manufacturers for meeting their own research and development and product optimization needs, or the formulated testing standards, are insufficient. The large number of upstream and downstream manufacturers involved in test platforms and standards are involved in the transformation of results from theory to practice. The standard centralized industrial units must organize a large number of vendors to conduct in-depth demonstrations and actively cooperate to promote the growth of this industrial technology.

3.2 Digital wind power technology development trends and needs

3.2.1 Intelligent wind power monitoring

The intelligent monitoring of wind farms can generate great commercial value. The specific requirements of such monitoring include: integrated intelligent sensing technologies for wind turbines and farms, wind data collection, transmission, storage, integration, fast search, and extraction technologies; inter-communication solutions that are compatible between different wind farm manufacturers and establishing a wind farm monitoring information model; and remote large-scale wind farm communication technologies and the development of wind farm communication protocols and data visualization display platforms to allow the seamless integration of wind farm information.

3.2.2 Wind power intelligent operation and maintenance

Intelligent wind farm operation and maintenance technologies are developing towards informatization and clustering. Through the deep integration of intelligent control, advanced sensing, and high-speed data transmission technologies, the operating states and working conditions of wind turbines can be comprehensively analyzed, and the operating parameters of the unit can be adjusted in real time to enhance the efficiency and reliability of wind power equipment operation.

The integration of wind power operation and maintenance with information technology includes the implementation of an Internet of Things Big Data platform covering wind farm operation data, meteorological data, power grid information, and wind power equipment operation information; strengthening intelligent wind turbine control and optimizing power generation through the coordinated control and comprehensive analysis of multiple wind farm groups; developing wind farm maintenance theory centered on reliability; maintaining the inherent reliability and safety of equipment in accordance with minimum maintenance resource consumption; confirming the preventive equipment maintenance requirement process using logical decision-making methods; and the mining of wind power big data and development of intelligent diagnosis technologies based on a cloud computing platform. The data analysis scope covers the wind farm from design and construction to condition monitoring, fault diagnosis, and the entire operation and maintenance process.

3.2.3 Intelligent wind turbine fault diagnosis

The current operation and maintenance of wind turbines adopt the “passive” mode for regular and post-fault maintenance. It is necessary to change this operation and maintenance mode, fully employ wind power status monitoring methods, and research early warning systems. Changing the “passive” maintenance of wind turbines to “active” would improve the efficiency of wind power operation and maintenance, and increase the revenue from wind power development. Current operating wind farms are equipped with a supervisory control and data acquisition system (SCADA) that contains historical data that have accumulated over many years of operation. To monitor the vibration state of wind turbines, new wind turbines are equipped with a vibration condition monitoring system (CMS). Wind power condition monitoring and intelligent early warning research have been conducted based on big data technology. Research on state prediction, wind turbine fault diagnosis methods, and vibration signal detection and analysis research can be conducted by combining the main control system of the unit with SCADA and CMS data, which would allow feature extraction and the precise positioning of key wind turbine components. Combining fatigue load analysis with intelligent control technology to monitor the health, diagnose faults, conduct life-cycle assessment, and dispose of wind turbines automatically has become a technical direction in which all manufacturers are investing.

3.3 Power-grid friendly technology development trends and needs

The form of access to wind power in China is developing from single centralized access to long-distance transport and a diversified approach, and decentralized access and microgrid applications are increasing. In the new application scenario, wind power will meet the needs of users more directly, and users will propose higher standards for the quality of wind power.

The development of distributed wind power applications in Europe and the United States is more mature than that in China; however, access standards are constantly improving in accordance with market development. For example, at the end of 2016 in the United States, the UL 1741 standard proposed a series of new requirements for fault ride-through, frequency support, and island protection of decentralized access power, and the technical direction and applicability of this action should be referenced in China.

Future wind and traditional power, energy storage, load, other new energy types, charging piles, and intelligent distribution protection systems will generate more and deeper interactions, and there will be a broad development space for operational control, information interactions, and security.

3.4 New wind power technology development trends and needs

The widespread utilization of renewable energy, such as wind power, is still in its infancy. Under low-carbon and environmentally sustainable development, new and novel wind turbine technologies will be developed in the future, and new materials and processes will continue to be implemented in wind turbines, enabling us to more efficiently and flexibly generate wind energy at a lower cost; for example, by developing variable flow technologies using silicon carbide (SiC), blade weaving technologies, and multi-impeller structures.

By the end of 2017, over 100 000 wind turbines were operating in China. According to the 20-year service life, by 2027, China will face the issue of having to decommission almost 10 000 wind turbines every year. Although suitable fault monitoring, operation, and maintenance technologies can effectively increase the service life of the unit, methods for disposing of decommissioned wind power equipment is an issue that cannot be ignored. At present, such research in this field is receiving little attention in China, and it is mostly in the exploration stage. For example, methods for the decomposition and recovery of blades and permanent magnet materials are being explored; however, the technical and commercial feasibility of these methods remains to be verified.

4 Conclusions

In recent years, relevant departments in China have organized research and statistical analysis concerning the amount of wind energy resources that can be developed technologically and economically in China. Owing to the advancement of wind turbine technologies, the available reserves of wind energy resources are expanding. If the current resource conditions are intensively developed, this technology can fully meet the current non-fossil energy indicators for 2030 [7], and the advanced experience of European and American countries also provides a good reference for China to meet its high-proportion, high-permeability renewable energy development goals.

Under the goals set by China's *Renewable Energy 13th Five-Year Development Plan*, a series of industrial policies were launched at national and local levels in 2017. Offshore and decentralized wind power are clear market orientations that provide many innovative ideas and openings for the technological development and upgrade of the wind turbine manufacturing industry. Under the guidance of the "Belt and Road" policy, China's wind turbines will also be implemented in overseas markets. With the increasing proportion of wind energy in the power system, power transmission and applications have become increasingly abundant, and the demand has become more and more specific, which will facilitate the healthy development and continuous technological advancement of China's wind turbine industry.

Low wind power prices are spreading among current domestic and international markets. In Morocco, India, Mexico, and Canada, the price of wind power has reached a minimum of 0.03 US dollars/kWh. In 2017, the world's first "no subsidy" offshore wind power project appeared in Germany, which improved the position of 3 GW offshore wind power in Europe. The sharp decline in wind power prices is putting tremendous pressure on the upstream and downstream industrial chains and reducing the potential for profits; nevertheless, the development of wind turbine technologies has also contributed to achieving this goal.

Based on the needs and characteristics of China's wind power development industry, the next development direction of China's wind turbine technology will be to actively compete in the international market, continuously improve the theoretical research of large-scale advanced wind turbines, improve the wind power equipment supply chain, allow innovative design and intelligent manufacturing to achieve an optimal combination, ensure the quality and reliability of wind turbines, explore and consolidate core competitiveness, and reduce homogenization competition. Wind turbine manufacturing enterprises will also become the main body of the technological innovation field to promote industrial progress with science and technology, and drive the industrialized development of wind power.

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