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Structural behavior of a wind power tower

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Abstract

As one kind of the clean energy, wind energy has satisfied more and more global electricity demand in recent years, and the design of the power and size of the wind turbine have increased much more than before. However, problems also appear with the rapid development of the wind power industry, and the collapse of the wind towers can produce hazard to people, even the death of the maintaining workers of wind turbines. The collapse reasons are mainly due to the insufficient bearing strength and the insufficient buckling strength, the weak points are always at the areas of the thickness change, the door opening and the connection part. The failure modes are generally related to the overall overturning, the tower failure and the blade failure. The collapse form of wind power tower under various loads has become the focus of an increasing number of investigations. This thesis analyzes the structure response of a simplified model of a wind power tower under the effect of wind and earthquake, checking whether the stress meets the requirement of the design strength according to the Chinese code.

Key words:

Clean energy, wind towers, structural behavior

Sommario

Come fonte di energia pulita, l'energia eolica ha soddisfatto sempre di più la domanda di elettricità globale negli ultimi anni, e la potenza e le dimensioni di progetto della turbina eolica sono aumentate molto più di prima. Tuttavia, anche vari problemi appaiono con il rapido sviluppo dell'industria eolica, e il crollo delle torri eoliche può produrre pericoli per le persone, fino alla morte dei lavoratori che mantengono le turbine eoliche. Le ragioni del collasso sono dovute principalmente all'insufficiente resistenza portante e al limite di instabilià. I punti deboli sono sempre nelle aree del cambiamento di spessore, in corrispondenza dell'apertura della porta e delle connessioni. La crisi strutturale è generalmente dovuta al rovesciamento complessivo della torre, all'avaria di una sua parte e alla crisi delle lame. Le varie tipologie di collasso delle torri eoliche sotto vari carichi sono diventate il fulcro di un numero crescente di indagini. Questa tesi analizza la risposta strutturale di un modello semplificato di una torre eolica sotto l'effetto del vento e del terremoto e verifica se lo sforzo soddisfa i requisiti di resistenza secondo il codice cinese.

Parole chiave:

Energia pulita, torri eoliche, comportamento strutturale

1. Introduction

1.1. Background and significance of wind energy

Nowadays, the population of the world grow rapidly, the problem caused by the fast developing of industry and the problem of energy crisis becomes clearer and clearer in the world. The deterioration of environment has even affected human life safety[1]. In the past years, the price of wind energy is quite expensive, but now the price of wind energy becomes more cost-competitive than the coal and gas[2].

As a non-renewable energy, the benefit of wind power generation is clearer and clearer. The sufficient, safe and clean energy supply is the guarantee of human economic development and social progress. The development of new energy is becoming more and more important. Wind energy is one kind of pollution-free renewable energy, widely distributed on land and sea, and its reserves are huge, and widely distributed on land and sea. Compared with traditional energy, wind power generation has the advantages of low cost, no carbon dioxide emission and easy installation[3].

The wind pushed boats up the Nile 7,000 years ago, windmills were used to pump water in China 2,000 years ago. Harnessing the wind power is not a new concept, the method of the ancients is still helping us to create renewable and sustainable energy on the electricity making. Wind energy generation can be mainly divided as two kinds: onshore and offshore. The onshore wind turbines are simply built on the land, use the wind energy on the wind open area. They can be built on fields, coastal areas, tops of mountains or even the backyard of houses. The first onshore wind turbine is dated back to the 19th century, and now the types of wind turbines from the horizontal axis wind turbines of all sizes turbines to the vertical axis wind turbines are shaped like fusilli pasta. The offshore wind turbines are the turbines built over the sea and far from the coast. The vertical wind turbines can also be installed on the sea but mostly installed on the existing offshore platform and make electricity directly to the offshore work stations[4][5]. To properly install onshore farms and provide clean energy generation, there is a required study of the terrain and wind currents that must be performed. Offshore farms enjoy a less troublesome inconsistency due to constant winds with higher speeds, providing a more reliable and efficient power generation.

Figure 1. An onshore wind farm located in Xinyang, China[7]

Figure 2. Offshore wind turbines in New Shoreham, United States[7]

Comparison of onshore and offshore wind power generation[6]:

Cost for installation:

The installation of onshore wind tower and additional infrastructure for energy transmission provide lower costs than offshore farms, the price of onshore wind energy is much cheaper. The price of onshore wind can be as cheap as 20 $/MWh until now, they said there would be a lower energy cost for 2030 because of the three times as many onshore wind farms installed than in 2018.

Due to the need for more installation materials and equipment, higher technical requirements and energy transmission infrastructure, Offshore wind installations are almost 20% higher than onshore. By 2019, offshore wind power costs have fallen 32% concerning 2018, estimating generation costs at 78 $/MWh. It is estimated that offshore wind power might be as cheap as fossil fuel by the year 2038.

Space required:

Onshore wind farms require land space usage to be installed and provide clean energy. To provide a continued flow of power generation, onshore wind turbines require a minimum distance of 150 m from any obstructions and 7 times the diameter of the rotor from each other.

Offshore wind power generation doesn’t need the installation for wind farms. The minimum required distance for offshore farms is at least 200 nautical miles from the shore and 50 feet deep into the ocean floor. Power density for offshore turbines oscillates around 1, requiring 2 for a 2 MW turbine.

Advantages:

Onshore:

- Lower installation costs, faster investment payback.
- Generated energy easily to be hooked to the grid.
- Lower maintenance cost.

Offshore:

- Higher potential for power generation due to faster and more stable winds.
- No noise pollution.

- Larger wind turbine than onshore wind turbine.

Disadvantages:

Onshore:

- Require a more careful analysis of terrain.
- Potential space can be more limited due to terrain costs and potential urban expansions.
- Heavy noise pollution.

Offshore:

- Higher installation cost and power transmission than onshore wind power.
- Underwater noises and turbines to the fauna over bodies.
- Expensive and not-easy performed maintenance.
- Longer time of energy restoration after a malfunction.

1.2. Literature review

As for the simulation of the resistance of the wind turbine under the load, the basic methods are the testing and numerical application. The numerical method is always done by the software, such as ABQUS, ANSYS. For the model construction, one is simplifying the wind blade and engine room as a mass point or an eccentric mass block, another is using a connection between the parts of the wind turbine. In addition, the translational mass and rotational mass are usually applied to the simplified particle to consider the rotation effect of engine room and wind blade. In the detailed simulation, most people always regard the wind blade as a variable section and stiffness component, use beam element or shell element to model. But there is little difference between shell element and beam element in structural analysis, shell element modeling can be used for further buckling analysis and other calculations. If want to study the wind turbine in detail, some components such as the door opening, are needed to be taken into consideration. If use the connection when model the structure of different parts, the constrained element is needed or the constrain is applied, the connection needs to be handled properly in case there would be a slippage between components.

The simplified modeling of the top of the tower saves the modeling steps, and it is widely used in the seismic and modal analysis of the tower under the static state of the fan. The detailed modeling of the top part of the tower can consider the coupling between the tower body and the blade and the aerodynamic effect of the blade operation. It has been found that the tower and blade vibration interact with each other. Ignoring the coupling effect may underestimate the tower top vibration under wind load, considering the coupling effect of the wind blade to the tower body will improve the accuracy of higher-order modal parameters. About the simulation of wind power tower:

Lobitz modeled the wind power support structure in the fixed coordinate system, and the wind turbine blade in the rotating coordinate system. Considering the eccentric effect on the rotor of wind power generation structure, the tower, engine room and blade were discretized into nodes. The mass, stiffness and damping matrix of wind power generation structure were calculated by finite element software NASTRAN[8].

Murtagh et al. modified the blade stiffness matrix to simulate the dynamic stiffening effect caused by fan blade rotation. At the same time, the detailed modeling was also in progress[9].

Kühn proposed a design method of wind power generation structure in offshore wind farm, introduced the modeling method of wind power generation structure. He divided the wind power generation structure into two parts: blade and tower. Based on finite element modeling, the tower was simulated by beam element. Because of its complex deformation, the blade would shimmy perpendicular to the rotating plane and swing in the rotating plane. The multi-body dynamic modeling could better consider the deformation in two directions. The coupling between tower and blade was realized by loads[10].

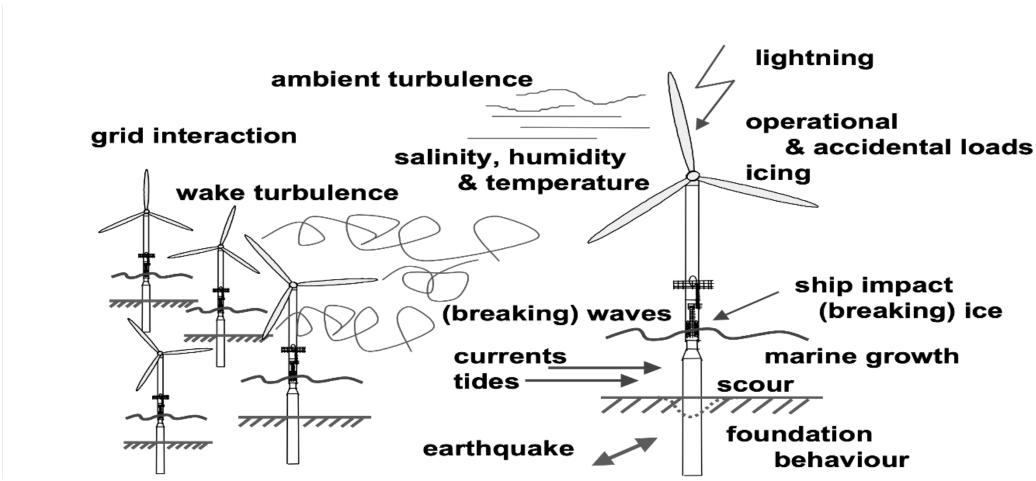


Figure 3. Offshore wind farm[10]

Bazeos et al. carried out detailed analysis of 450 KW wind power tower. In the aspect of detail modeling, Bazeos and others' work was mainly reflected on the door opening of the wind power structure and the flange of tower connection. The element used was higher order. The tower, the stiffener and flange at the door opening were all solid elements. The drawback was that although Bazeos and others dealt with local details more finely, they did not model the blade of wind power structure[11].

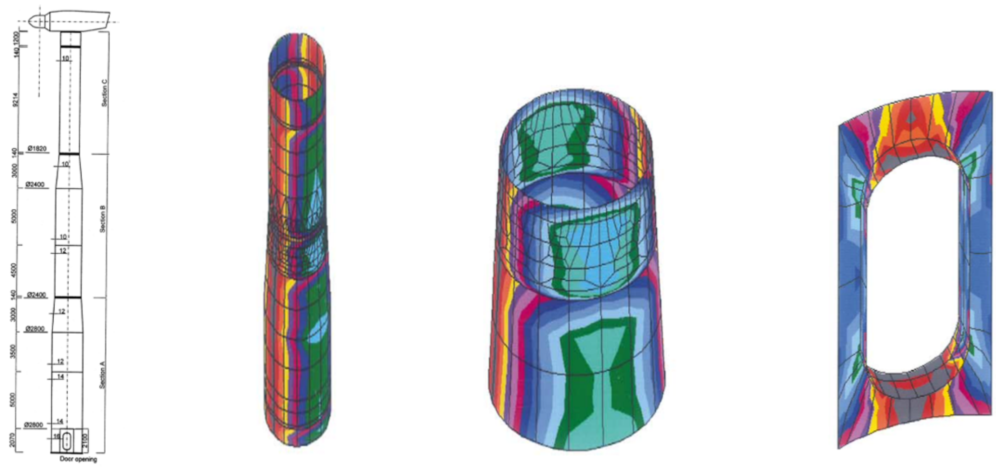


Figure 4. Detailed modelling of wind power tower[11]

Based on horizontal axis wind turbine, Dai and others of Tongji University briefly introduced the structure type of wind power tower and recent wind farm accidents, and then summarized the research status of dynamic performance, wind resistance and earthquake resistance, health monitoring and vibration control of wind power tower. It was found that the vibration of the structure was an important factor leading to the instability of the wind power tower structure, and it was necessary to explore the economic and effective broadband damping technology[12].

Chen of Kunming University of technology, relying on a wind power plant fan transformation project, changed the diameter of the fan from 50m to 52 meters to study the dynamic characteristics of the tower before and after the transformation. First, using the commercial software AWB, he studied the dynamic characteristics of the fan tower from the point of view of numerical method. Then, the dynamic characteristics of the system were studied from the experimental point of view. Finally, the dynamic characteristics of the fan tower were studied according to the results of the experiment and numerical method. From the theoretical analysis of the stress and displacement of the tower top and the experimental data processing results, he obtained that the results showed that the stress and displacement of the top of wind tower were proportional to the square of wind speed [13].

Jiang of Shenyang University of technology modeled a 3 MW horizontal-axis wind turbine, did the fluid-solid interaction analysis of the wind turbine by the finite element software ANSYS, and obtained the response of the flow field and the structure under the rated wind speed. He analyzed the response results of the structure under different wind speeds, he concluded that: the maximum displacement of the blade appears in the tip, and the maximum stress appears in the middle of the blade. The maximum displacement of the tower appears at the top and the maximum stress appeared at the bottom. Under the condition of modal analysis and seismic response analysis, he concluded that: the influence of longitudinal seismic action on the tower was greater than that of transverse seismic action [1].

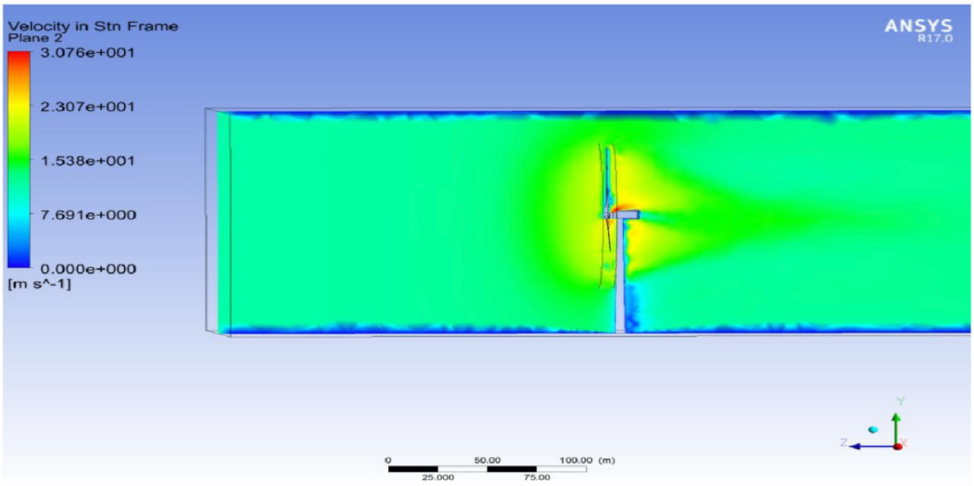


Figure 5. Velocity cloud at rated wind speed[1]

Ma and Huang of Tongji University analyzed the natural vibration characteristics of 3MW wind power tower in Laizhou Bay by using the measured environmental pulsation. The theoretical and measured values were compared, and the influence of prestressed anchor bolt foundation and reverse balance flange on the stiffness and frequency of wind turbine was analyzed[14] [15].

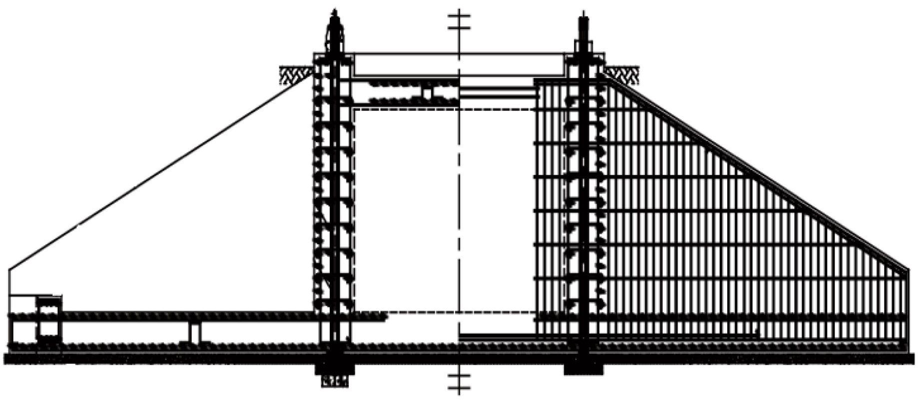


Figure 6. Prestressed anchor bolt foundation[15]

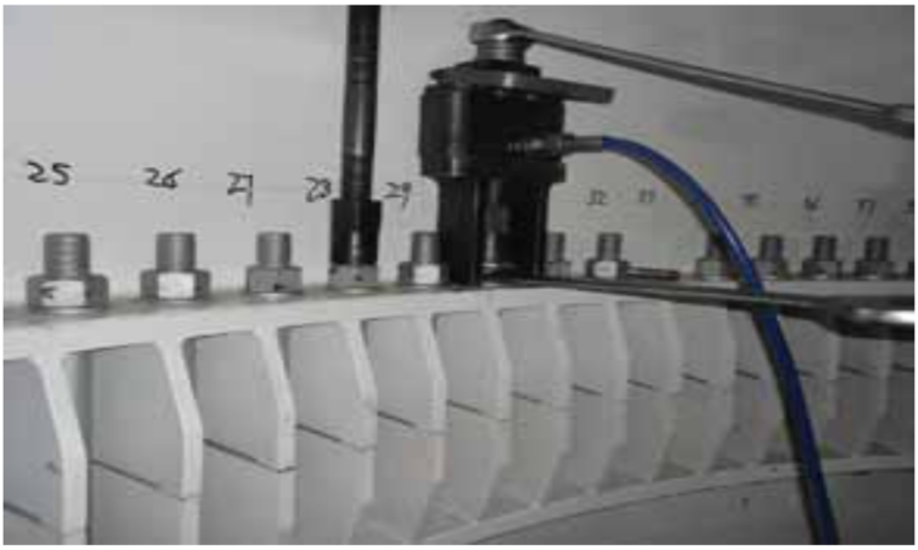


Figure 7. Reverse balance flange[15]

Zhao and Lv analyzed the static strength of the tower by using the finite element software. The stress, strain and displacement of the tower under the limit wind load are calculated accurately. It was verified that the tower meet the requirements of strength and stiffness, which provided an effective theoretical basis for the structural dynamic design of the wind turbine tower[16].

Ai et al. used CFD method to simulate the aerodynamic force of two-dimensional airfoil, and compared the wind pressure coefficient and flow field characteristics of airfoil. The time history sequence points of 1.5 MW wind turbine's downwind fluctuating wind at different heights were obtained by MATLAB software simulation, and the transient dynamic analysis of the tower was carried out by the load of the wind wheel[17].

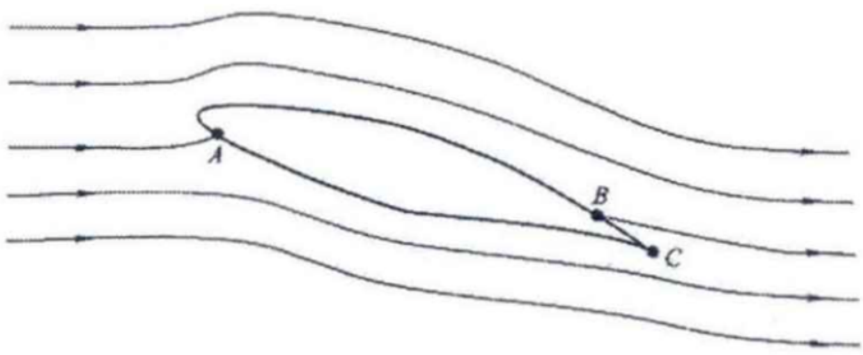


Figure 8. Flow around an ideal airfoil[17]

Aiming at the instability problem of wind turbine caused by the vibration of wind turbine tower, Cheng established the three-dimensional structure dynamic model of tower in SolidWorks. ANSYS software was used to analyze the vibration characteristics and wind-induced response of the tower in extreme environment.

The results showed that the first three order formation of the tower was transverse bending with small displacement. The fourth mode produced transverse and torsional deformation, and the stress change and vibration amplitude were larger than other modes. The fifth mode appeared torsion. These results provided a favorable basis for the vibration characteristics of the tower[18] [19].

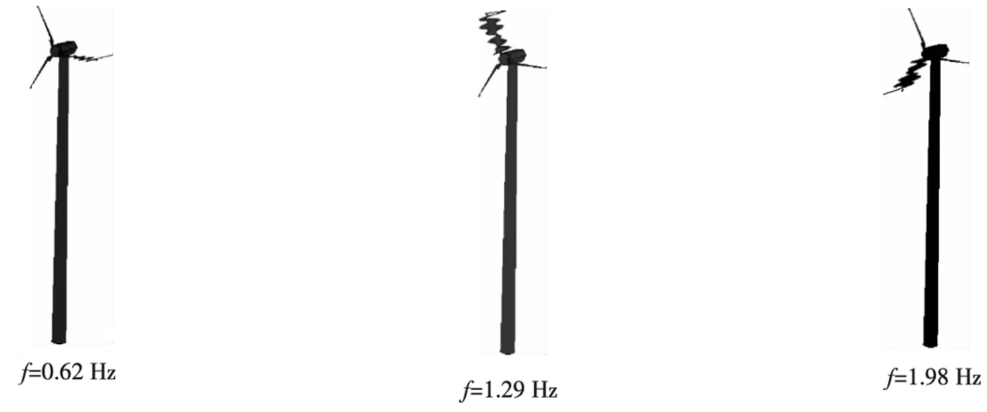


Figure 9. The first three modal vibration[18]

Figure 10. The first three modal shape[18]

Most of scholars simulate the wind power tower by inputting the wind loads and the earthquake waves in the finite element software respectively, it can get the almost real results. But for the coupling of wind and the earthquake in the limit state, we still cannot get clearly.

2. Wind power generation in the world

From the report of Global wind energy council[2], 2019 is a big year for the wind industry, the total installation of onshore and offshore wind energy generations exceeds 60 GW again historically, where the onshore wind generation reaches 54.3GW, the offshore wind generation reach 6.1 GW that making up 10% of the global new installations.

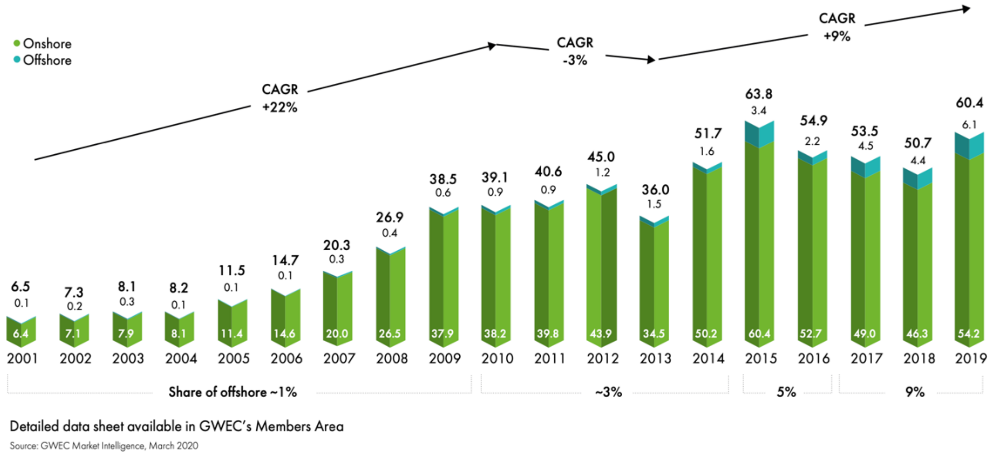


Figure 11. Historic development of new installations (onshore and offshore)[2]

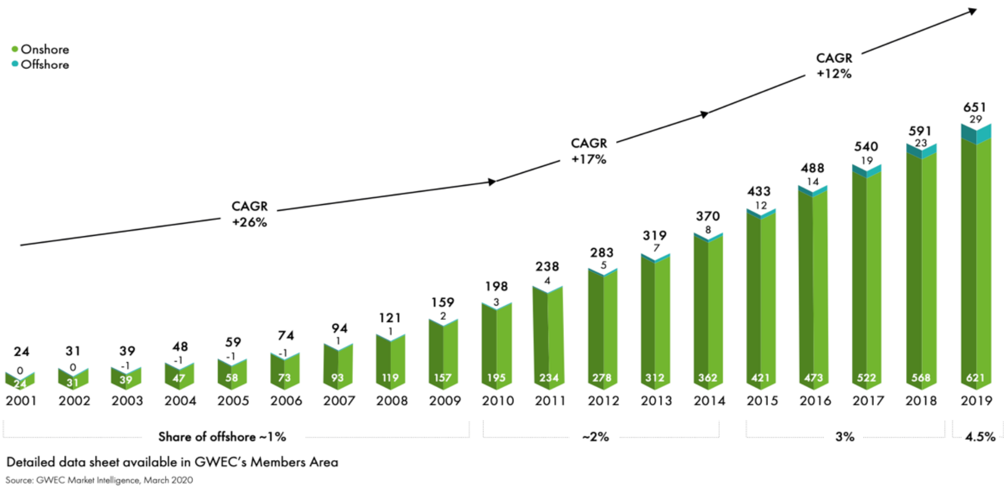


Figure 12. Historic development of total installations (onshore and offshore)[2]

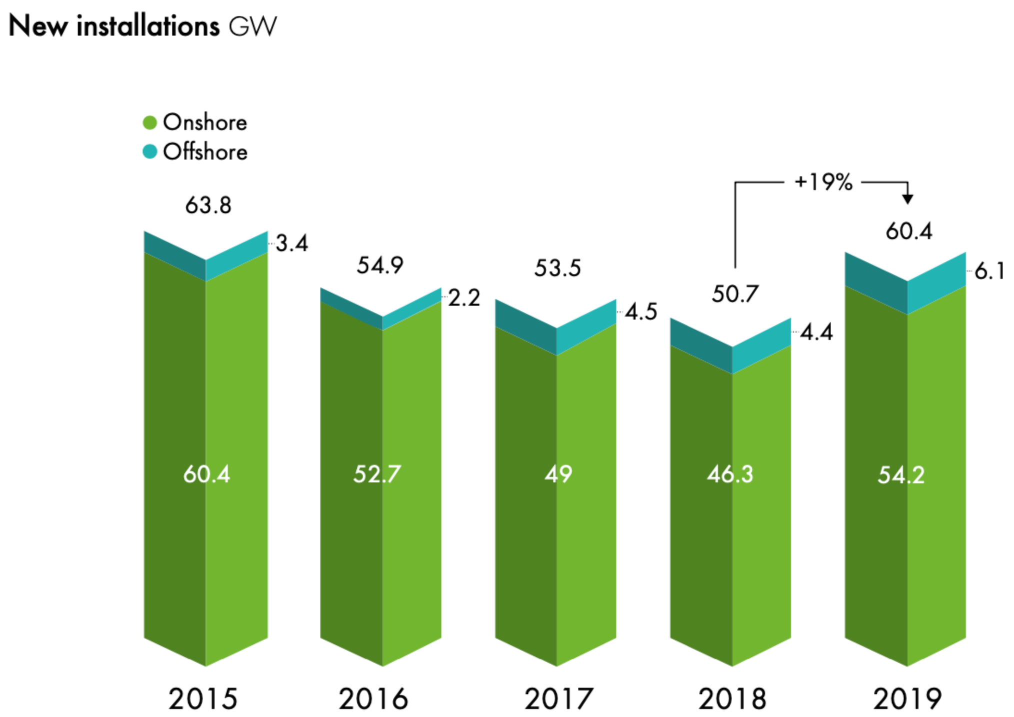


Figure 13. New installations from 2015 to 2019 (onshore and offshore)[2]

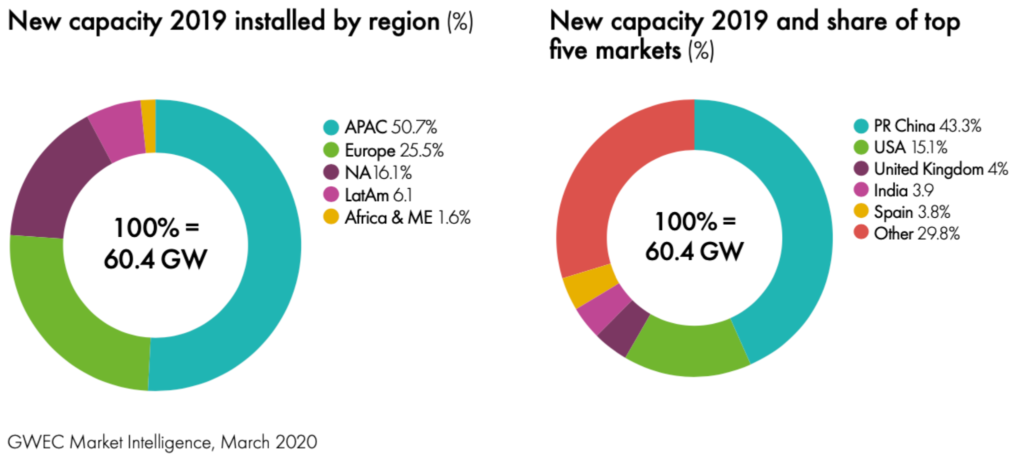


Figure 14. New capacities[2]

The total installation of wind power generations reaches 651 GW in 2019, and there is 19% growth of new installations in 2019 compared to 2018. Asia Pacific takes the lead in the global wind power development which accounts for 50.7% in 2019, then it is Europe(25.5%), North America(16.1%), Latin America(6.1%) and Africa& Middle East(1.6%). The top five market in the world in 2019 for the new installations are China, the US, United Kingdom, India and Spain, then the left part takes about 30 percentage.

In Europe, the installed capacity of wind power has been 169 GW in total until December of 2107. 15,680 MW of wind power was installed in 2017, accounting 55% of all new power capacity, and the wind power generated 336 TWh electricity, enough to supply 11.6% of the electricity consumption of Europe. The wind power seems like to continue to increase in Europe in the following years[20]. According to the report of European Environment Agency, wind energy will play a major role in achieving the target of the renewable energy in Europe. From the estimation of European Wind Energy Association, 230 GW wind capacity will be installed in Europe by 2020, including 190 GW onshore and 40 GW offshore. This would produce 14-17% of the electricity in Europe, avoiding 333 million tons of carbon dioxide per year and saving Europe €28 billion a year in fuel costs, and the wind energy are gradually playing an important role in Europe from the report of Iberdrola[21].

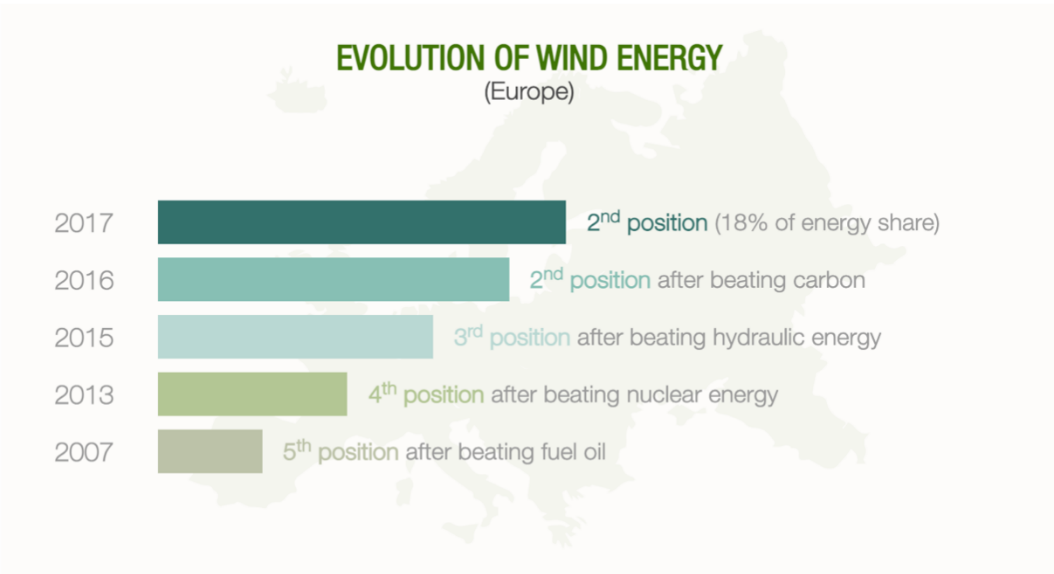


Figure 15. Evolution of wind energy[22]

In Asia, Wind power are taking a big part in the energy industry of Asia, and one of the key sources of renewable energy in the region. The installed capacity of wind power in Asia has been 175,831 MW until 2016. Asia is also the fastest growing region in the industry of wind energy, having increased its installed capacity by 33,858 MW in 2005 (a 24% increase over 2014). China, with 145,362 MW of installed capacity, is the world's largest generator of electricity from wind energy. India is the second largest in Asia with an installed capacity of 25,088 MW. Other key countries are Japan (1,394 MW), Taiwan (188 MW), South Korea (173 MW) and the Philippines (33 MW). The spread of wind power has dropped behind Europe so far. But according to IRENA, Asia would account for more than 50% of global onshore wind power installations by 2050[23]. According to the report 'future of wind' of International Renewable Energy Agency, IRENA predicts the wind power industry will make a "prominent shift" toward Asian waters, with the region coming to "dominate global offshore wind power installations. The turbine size for onshore applications will also increase, from an average of 2.6 megawatts (MW) in 2018 to 4-5 MW for turbines commissioned by 2025. The installation of wind power generation will likely grow to 15-20 MW in the future. By 2050, floating wind farms would cover around 5-15% of the capacity of global installation (almost 1,000 GW)[24].

Asia wind energy capacity (MW)[1]												
#	Nation	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1	China	2,599	5,912	12,210	25,104	44,733	62,733	75,564	91,412	114,763	145,104	
2	India	6,270	7,850	9,587	10,925	13,064	16,084	18,421	20,150	22,465	25,088	
3	Japan	1,309	1,528	1,880	2,056	2,304	2,501	2,614	2,669	2,789	3,038	
4	South Korea	176	192	278	348	379	407	483	561	609	835	
5	Taiwan	188	280	358	436	519	564	564	614	633	647	
6	Pakistan[3]	–	–	–	–	–	–	–	–	–	255	
7	Thailand	–	–	–	–	–	7	112	223	223	223	
8	Philippines	–	–	–	–	–	–	–	66	216	216	
9	Iran	47	67	82	91	91	91	91	91	N/A	N/A	
10	Sri Lanka	–	–	–	–	–	–	63	63	N/A	N/A	
11	Mongolia	–	–	–	–	–	–	–	50	N/A	N/A	
–	Rest of Asia	–	–	–	–	–	–	71	87	–	167	
World total capacity (MW)		10,589	15,829	24,395	38,960	61,090	82,387	97,983	115,986	141,902	175,831	

Table 1. Wind energy capacity in Asia[23]

In USA, Wind power is one part of the energy industry and has developed quickly in resent yeas. In 2020, 337.5 TWh were generated by wind power, took 8.42% of all generated electrical energy in the USA. Wind power exceeded hydroelectric power as the largest renewable energy source generated in the USA in 2019. The total installation of wind power capacity is 122478 MW in USA until 2021, which is just behind China and the Europe. There largest growth of capacity about wind power is in 2020, where 16913 MW of wind power was installed. Then in 2012, 11895 MW wind capacity, representing 26.5% of the new power capacity was installed. 19 states had exceeded the capacity of 1000 MW by September 2019, the total installation of Texas, Iowa, Oklahoma, Kansas, California, was over half of all wind energy in USA. Texas, with 28843 MW of capacity, about 16.8% of the state's electricity usage, had the most installed wind power capacity of any state at the end of 2019. Texas also had more capacity under construction than any other state currently has installed. The state generating the highest percentage of energy from wind power is Iowa, whose capacity are over 57% of total energy production, while North Dakota has the most per capita wind generation. As the largest win farm, Alta Wind Energy Center is the largest domestic wind turbine manufacturer in the United States, with a capacity of 1548 MV[25].

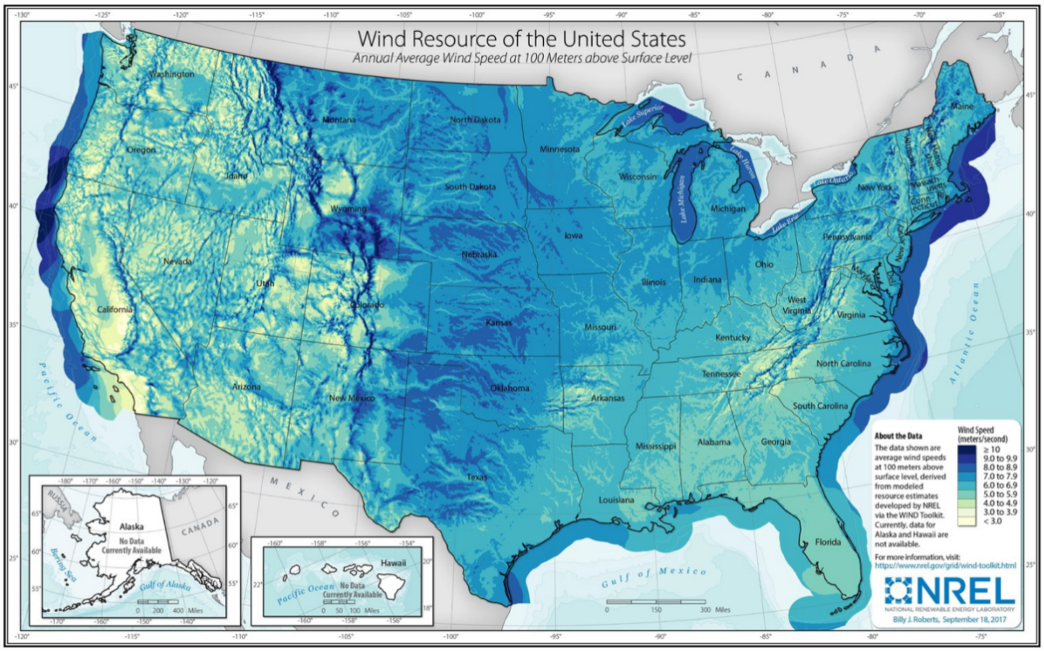


Figure 16. Map of wind source in USA[25]

Project	Capacity (MW)	State
Alta Wind Energy Center	1548[8]	California
Los Vientos Wind Farm	912[13]	Texas
Shepherds Flat Wind Farm	845[14]	Oregon
Meadow Lake Wind Farm	801[15]	Indiana
Roscoe Wind Farm	781[16]	Texas
Horse Hollow Wind Energy Center	736	Texas
Tehachapi Pass Wind Farm	705	California
Capricorn Ridge Wind Farm	662	Texas
San Gorgonio Pass Wind Farm	619	California
Limon Wind Energy Center	601[17]	Colorado

Table 2. The largest ten wind farm in USA in 2018[25]

Latin America had been developing well in the area of wind power, but now it is facing a slowdown. Political challenges have arisen in different markets, making growth patterns uneven across the region, in high potential markets such as Mexico, Argentina. According to the study from IHS Emerging Energy Research (EER), Chile and Mexico are expected to have added more than 3.7 GW of wind power from 2010 through the end of 2012. Brazil accounts 70% wind market of the Latin America, but it just dug a small part of the wind power potential. Demand for diversity of supply is expected to increase in wind generation of Latin America because of the dropped cost through local manufacturing. Under the condition of the well-developed technology of wind energy generation and the aim to grow local industrial activity, developers and governments are gradually turning to wind energy from other renewable energy[26].

Under the economic crisis of the world, Latin America was relatively unaffected by the recession, and there is great growth. Brazil experienced a 4.5 percent power demand growth rate between 2003 to 2008, while Mexico saw a 3.8 percent growth rate from 2003 to 2007. Chile was also unaffected by the recession. The installed generating capacity in Latin America grew 50 percent, adding 703 MW of wind power in 2010. As of February, Brazil has approximately installed 1.6 GW capacity of wind power, the installed wind generation capacity of Mexico has surpassed 1 GW, and Chile has almost 300 MW[26].

In Africa, the wind power has surpassed the hydropower in the latest years, which was the longest-standing and largest green energy source used in Africa's electricity supply industry of the renewable energy. But the wind industry in Africa is still small and concentrated, substantial progress has been observed over the last ten years. In August 2017, the total capacity was recorded at 4.1 GW, the equivalent of four conventional nuclear power plants. This figure is slightly below the 1% mark of the cumulative global capacity according to the Global Wind Energy Council (GWEC) but still an almost 300% increase from 1.1 GW in 2011. The South African REIPPPP, launched in 2011, is mainly responsible for this marked expansion[27]. But there are also several challenges faced by the industry:

Policy challenges

As we know, the wind industry needs the clear strategic and regulatory framework to go with. Just the North African countries and South Africa made a clear plan to boost the industry. Under the Paris Accord, 34 African nations of the 55 African nations in Africa have made the energy targets, but the plans they made are still quite differs.

Technical challenges

Like the sun, wind energy is an intermittent source of energy that is not easy to predict. In addition, wind energy has no storage capacity. Because electricity itself cannot be stored, wind power needs a stable supply chain. Africa is composed of many small countries. When the wind blows, the wind power output of a country needs to be used, no matter how much is left. Therefore, the integration of wind power system in Africa is a problem to be solved.

Economic challenges

It is important to assess the economic viability of wind power generation for evaluating the potential of growth of the wind industry. The cost of renewable energy has decreased in recent years, but capital costs are still the major financial issue. The average cost of energy (LCOE) for wind globally may have dropped to $59 per MWh but capital costs still represent most of the budget, in many cases at least 75%. The intermittency of wind energy implies that we need the significant back-up plans to satisfy the demand of electricity.

In 2012, the wind power generation just represents only 2.5% of the production of grid-based power generation in Africa, which was 158 GW in Africa. McKinsey and the IEA predict that the population of Africa in the south of Saharan will double by 2040, and the economy will increase four times than now. The energy demand will increase sharply by around 80%. From this analysis, we can get that although the potential of wind energy in Africa is enormous, they do not make full use of these resource, and the sector lacks ambition. What could transform the industry is that they need a bold and holistic vision that would look at and integrate aspects together, as well as initiatives to boost knowledge and regional capabilities. With a strong will and suitable plans, Africa will make a big step in the area of wind energy[27].

		Areas with CF greater than 30%	Areas with CF greater than 40%
Region	Total area (km^2)	TWh/year	TWh/year
Central Africa	5,317,718	1,576.7	578.3
Western Africa	5,006,014	1,692.2	58.8
Eastern Africa	6,225,847	30,860	16,580.5
Southern Africa	6,555,480	10,011.1	1,707.3
Northern Africa	6,784,934	22,500.9	6,919.9

Table 3. Wind energy potential in Africa[27]

3. Wind power generation in China

3.1. Capacity of wind energy in China

Due to the largest installed capacity and the continuous and rapid growth of new wind power facilities, China has become a major wind power development country.

China has vast land and abundant wind resources: it is estimated that China's land-based exploitable capacity is about 2380 GW and its offshore exploitable capacity is about 200 GW. By the end of 2020, wind power has become the third largest source of electricity in China, accounting for almost 12.8%. In 2020, China will become a big wind power generation country higher than the United States. In the United States, however, the capacity factor for wind power is much higher. The government has promised to increase the share of non-fossil fuels in primary energy consumption to about 25% by 2030. By the end of 2020, the Chinese government has drawn up a roadmap for the total installed capacity of wind power and solar energy to reach 1200 gigawatts by 2030. China has made wind power a key component of national economic growth. Some experts say China can achieve carbon neutrality by 2060 and peak emissions by 2030[28].

Year	Capacity (MW)[17]	Production (GWh)[18]	Capacity factor
2018[19]	184,260	366,000	22.70%
2019[20]	210,050	405,700	22.00%
2017	163,670	305,700	21.30%
2009	16,000	26,900	19.20%
2016	149,000	241,000	18.50%
2005	1,260	1,927	17.50%
2013	91,424	134,900	16.80%
2010	31,100	44,622	16.40%
2015	129,700	186,300	16.40%
2006	2,599	3,675	16.10%
2012	75,000	103,000	15.70%
2014	114,763	153,400	15.30%
2008	12,200	14,800	13.80%
2011	62,700	74,100	13.50%
2007	5,912	5,710	11%
2020	282,650	466,500	

Table 4. Wind power in China[28]

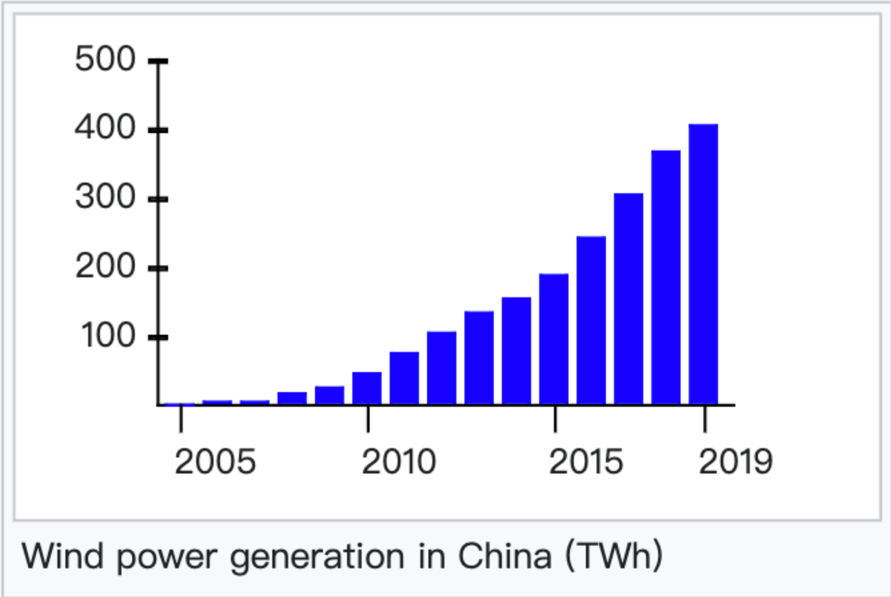


Figure 17. Wind power generation in China[28]

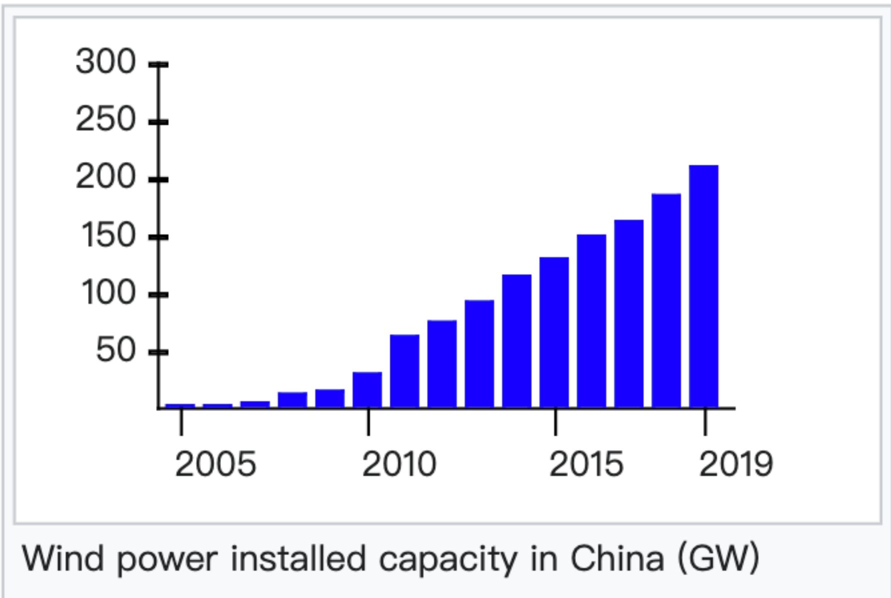


Figure 18. Wind power installed capacity in China[28]

3.2. Development of onshore wind power

3.2.1. Development history of onshore wind power generation

Since 1950s and 1960s, China began to study the wind turbine, but it is still in the exploratory stage. In the late 1970s, researchers began to study small-scale off grid wind turbines, aiming to solve the problem of power transmission for islands and remote villages. In the 1980s and 1990s, China's wind power industry began to boom for the first time, and many related policies were introduced. In 1986, China's first wind farm, Malan wind farm in Rongcheng City, Shandong Province, was completed and put into operation. In 1989, China began to build the wind farm with more than 100 KW. In 1994, the total installed capacity of Dabancheng wind farm in Xinjiang reached 10 MW, becoming the first wind farm with an installed capacity of 10000 kW in ChinaIn 1996, the former State Planning Commission launched "Chengfeng plan", "double plus project" and "national debt wind power project", which made China's wind power industry enter the stage of scale development[29].

Since the beginning of the new century, China's wind power industry has been developing rapidly. Since 2005, the total installed capacity has increased by more than 100% for six consecutive years. By the end of 2010, China's total installed capacity of wind power has surpassed that of the United States, ranking first in the world. In 2009, the "new energy industry planning" was issued, which determined that seven 10 million-KW wind power bases will be established in Gansu, Inner Mongolia, Xinjiang, Jilin, Hebei and Jiangsu. In 2020, the total installed capacity of the seven bases will reach 170 million KW[30].

3.2.2. Related technology of onshore wind turbine

Nowadays, the operation modes of wind turbines are mainly the three kinds: joint complementary, independent operation and grid connected operation. The wind turbine and generator are the tower main parts of wind power generation to converse the wind energy. Based on that, the control of the power and speed of the wind turbine and generator is the key technology of wind power generation. The constant pitch stall adjustment, variable pitch adjustment and active stall adjustment are three main methods to control the wind turbine and generator in China[31].

About the generator grid connection technology of China, it mainly includes the direct grid connection, the quasi-synchronous grid connection, the step-down grid connection and the SCR soft grid connection. The direct grid connection mode is still the mainstream in China because of its simple and easy operation, and it also does not need synchronous equipment and whole step operation, but the impulse current and voltage drop of grid connections are large. About the wind power generation systems in China, the constant speed constant frequency wind power generation system normally adopts two sets of large and small power generation systems, small capacity wind turbines generate power under the low wind speed, they are connected to the grid under the high wind speed. The variable speed constant frequency wind power generation system can be more flexible to optimize the operation conditions, the efficiency of electricity making of system also grow, the power generation efficiency of the system can reach 60% ~ 70%[32].

In addition, in terms of wind power grid simulation technology, China Electric Power Research Institute and other research institutes, Tsinghua University and other colleges and universities have established large-scale wind power simulation laboratory, which give the support of the strong simulation technology ability and relevant detection ability. Some companies of wind power generation in China such as ‘Gold Wind’, also make obvious technical progress in grid connected adaptive control of wind turbines and other technology fields[33].

3.2.3. Support technology of onshore wind turbine

There are three types of fan foundation: gravity foundation, pile foundation and rock bolt foundation. Gravity foundation is generally reinforced concrete structure, suitable for flat terrain, single layer of soil, is a typical shallow foundation. The foundation and the tower are connected by pouring through the foundation ring. The structure is simple and heavy, so it needs to be poured on site. Pile foundation is a kind of structure which distributes the stress of surface structure to the underground structure. The construction period is long, and the quality control is difficult. The advantage is that the foundation scale is smaller than gravity foundation and occupies less underground space. Rock bolt foundation is mostly used in rocky soil, mountainous terrain and other complex environment, the anchor is driven into the rock soil to fix.

Figure 19. Gravity foundation[42]

Figure 20. Pile foundation[42]

Figure 21. Rock bolt foundation[42]

3.3. Development of offshore wind power

3.3.1. Coastal wind energy resource

Up to now, the onshore wind power generation has been developed well, the technology is also getting mature. Then, many enterprises begin to move their attention to the offshore wind energy generation. Offshore wind generation mainly converse the wind energy over the sea, it has these advantages: no land occupation, high offshore wind speed, constant wind source, small turbulence intensity, large wind power generation capacity of wind turbines. Therefore, offshore wind energy generation becomes a new way to use wind source.

The sea has much better condition than the land, the key point is the size of the blowing wind. Statistically to say, the offshore wind speed of 10 km sea area is 20% higher than the onshore wind speed. The total annual generation capacity of offshore wind turbines is about 70% higher than the onshore wind turbines under the normal calculation. At the same time, the wind speed does not change too much all year round and there is no onshore calm wind period, so the offshore wind turbines is more time-saving about the electricity generation[34].

3.3.2. Distribution of coastal wind energy resource

The coastline of China is about 18000 km long, there are more than 6000 islands. Offshore wind energy resources are mainly concentrated in the southeast coast, its adjacent islands, and the wind energy density is basically more than 300 W/m^2. Taishan, Pingtan, Dachen, Shengsi and other coastal islands can reach more than 500W/m^2, of which the wind energy density of Taishan island is 534 W/m^2, which is the place with the largest recorded wind energy resources in China. According to the survey results of wind energy resources, the development potential of offshore wind power in China is about 200 million KW at the depth of 5-25 m and the height of 50m; The development potential of offshore wind power is about 500 million KW at the depth of 5-50 m and the height of 70 m[34].

China is rich in offshore wind energy resources, which mainly benefits from the activities of tropical cyclones in summer and autumn and the influence of cold air in North China in winter and spring. Due to the different geographical location and terrain conditions, the offshore wind energy resources of each coastal province and city also present different characteristics. From a nationwide perspective, the wind speed in the direction perpendicular to the coast basically increases with the increase of offshore distance. Generally, the wind speed increases more obviously in the areas closer to the coast. When the distance exceeds a certain value, the wind speed basically does not increase. Parallel to the coast, the area with the most abundant wind energy resources in China appears in the Taiwan Strait, showing a decreasing trend from the South and north sides of the area.

In order to make effective use of coastal wind energy, China divides coastal areas into three levels[35]:

The first level is "wind energy rich area", that is, the area where the annual average effective wind energy density is greater than 200 W/m^2 and the annual cumulative hours of effective wind speed (3-20 M/S) are greater than 5 000 H.

The second level is "wind energy rich area", that is, the area with wind energy density of 150-200 W/m^2 and annual cumulative hours of effective wind speed of 4000-5000 H.

The third level is "wind energy utilization area", which is the area with wind energy density of 50-150 W/m^2 and annual cumulative hours of effective wind speed of 2000-4000 H.

Compared with Europe, the wind power industry of China started late. With the increasing environmental pollution and increasing social power consumption, the Chinese government gradually began to pay attention to the use of energy, and increased the support for wind power enterprises. In 2007, CNOOC started the construction of China's first offshore wind farm. Its new energy company, together with CNOOC engineering company and Goldwind technology, established China's first offshore wind power demonstration project in Liaodong Bay, Bohai Sea. The project adopts foreign advanced technology, and the 1500kW wind turbine is produced and manufactured by local enterprises, which was officially put into use in 2007. Subsequently, between 2009 and 2010, local enterprises under the guidance of the Chinese government successively carried out the construction of a few offshore wind power projects, including Longyuan Jiangsu Rudong intertidal experimental 32.5 GW wind farm, Donghai Bridge 102gw offshore wind farm, etc. The 102 GW offshore wind farm of Donghai Bridge built in 2010 is the first real wind farm in China, which provides a lot of practical experience for the construction of other offshore wind power plants in China[34].

3.3.3. Utilization of coastal wind energy resource

In the recent years, China begins to use the wind energy of the eastern coastal areas. For example, Fujian Province gets much wind resource due to the "narrow pipe effect" of the Taiwan Strait, and has built many wind farms in Pingtan, Dongshan, Putian and Zhangzhou. By the end of 2018, seven wind power projects have been completed and put into operation in Fujian Province, with a total of 176 wind turbines installed, a total installed capacity of 233.75 million KW and a total power generation of 30.4 billion KWh. Jiangsu, Shanghai and other coastal areas are also rich in wind energy resources and have built megawatt wind power bases[36].

Region	Cumulative grid connected capacity [MV]	Construction scale [MV]
Tianjin	100	200
Liaoning	---	100
Hebei	---	500
Jiangsu	3000	4500
Zhejiang	300	1000
Shanghai	300	400
Fujian	900	2000
Guangdong	300	1000
Hainan	350	---
Total	5000	10050

Table 5. Offshore wind power in China[36]

Based on the numerical weather forecast and artificial neural network, China has established a wind power prediction system to predict the wind power of the wind farm in the future.

In order to make a better use of offshore wind energy, Chen Fei and others analyzed the distribution form of Lianyungang by using the past 30 years' meteorological data. They found that the wind speed in Lianyungang is steady, and it has a broad development prospect[37]. Mao Huiqin and others analyzed the wind energy resource of Guangdong Province and its coastal areas by using the past data of 86 meteorological stations and temporary observation data of 72 wind energy towers in coastal areas[38]; Yang Lifen and others have analyzed the wind energy resources of Longkou by using the observation data of the ocean station. The result showed that the annual average wind energy density of Longkou was 377 W/m^2, the annual average effective hours was 7589 h, and the main wind direction was relatively significant, which was suitable for wind power generation[39].

3.3.4. Support technology of offshore wind turbine

If the wind tower wants to survive in strong wind, a good foundation is needed. It can not only provide the support to the tower structure, but also limit the displacement of the tower. According to the different support technology of offshore wind turbine, there are two types of support: bottom fixed support and floating support. However, with the development of wind farm to deep sea area, floating wind turbine foundation has gradually become a new type of foundation on the sea[40].

Bottom fixed support

1. Gravity foundation

It stands on the sea mainly depending on its self-weight, use a reinforced concrete caisson structure which is generally suitable to the 0 ~ 10 m water area.

Figure 22. Gravity foundation[40]

2. Single pile foundation

The single steel pipe pile foundation is composed of a steel pipe pile with a diameter of 3-5 m, which is suitable for the water area less than 25 m. For soft soil foundation, hammer driving pile method can be used. The method of drilling can be used for rock foundation, and large diameter bored pile can also be formed in rock foundation. It is commonly used in the offshore wind turbine construction now, but the technology of the kind of foundations is still not at a mature level because of some collapse case these years.

3. Multi pile foundation

It is also called group pile high pile cap foundation, which is composed of foundation pile and upper cap (including concrete cap and steel cap), is suitable for 5 ~ 20m water area.

4. Tripod foundation

Three steel pipe piles with medium diameter are located on the seabed and buried 10 ~ 20 m below the seabed. The three piles are evenly arranged in an equilateral triangle, and the top of the pile is supported by a steel sleeve to support the upper tripod truss structure. The self-weight of the foundation is light, the stability of the whole structure is good, and it is suitable for the water area of 15 ~ 30 m.

Figure 23. Tripod foundation[40]

5. Jacket Foundation

A steel cone platform space frame, with steel pipe as bone ribs, is welded on land first, then drifted to the installation point, and the steel pile is driven into the sea floor from the conduit, which is suitable for water within 5-50 m.

Suspended support

It is a new type of foundation, also known as suction foundation or negative pressure tube foundation. It contains the single tube foundation and multi tube suction caisson foundation. It is applied to the various water depth conditions and wind fields with sandy soil or soft clay geological conditions.

Floating foundation

It is normally applied to the deep water, which is deep than 50 m, and is a box platform floating on the sea. Its platform is anchored to the seabed by anchoring system.

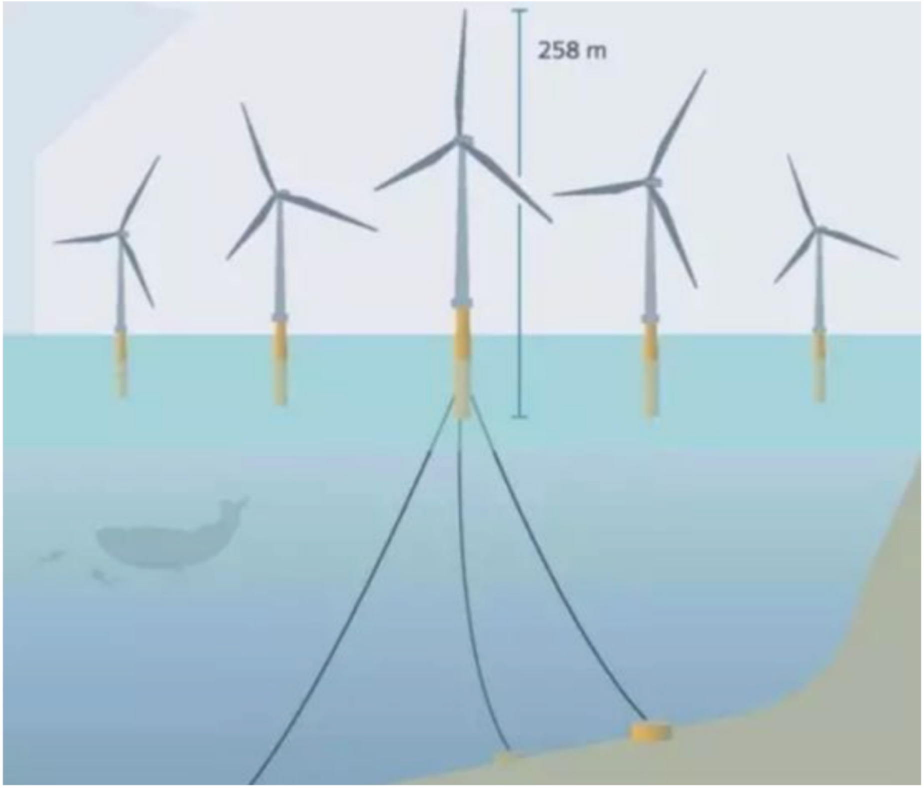


Figure 24. Floating foundation[40]

3.4. Problems and challenges of wind power generation in China

Although the wind energy industry of China is booming these years, there are still some problems in the development of wind power:

1. Lack of independent research and design capability

With the rapid development of wind power industry of China, many enterprises, in order to quickly have the wind turbine production capacity and purchase the license of foreign manufacturers, have very weak independent research and design ability and lack of basic research accumulation and talents, which leads to a large gap between the product quality and reliability and the mainstream foreign products, and once appeared the embarrassing situation of high installed capacity and low power generation. In recent years, this situation has been greatly improved, but the independent research and design capability is still seriously insufficient, some key design and manufacturing technologies of complete machine and parts still rely on foreign countries, and the homogenization competition of low-level technologies is still very serious.

2. Curtailment of wind power

The absorption of the large-scale wind power is the big problem in the world, China is also included. China has been working on the construction of the wind farm these years, so many big wind farms are constructed such as in Xinjiang and Gansu. But the areas with abundant wind power resources are generally backward in economy, the demand for the electricity is not so large that the power cannot be used on the spot. Abandoning and limiting of the power is getting worse.

3. Weak power storage technology

As an emerging industry, the lack of invest of the research and design at the beginning cause the immature storage technology of wind power. As mentioned above, the abandoning of power is the big problem now, which makes the needs clearer for the storage method of the electricity. Although China is increasing the capital investment now, the energy storage technology is still not good enough.

4. Problem of wind power integration

Easy to know, the integration of wind power is one important technology that is used now, the instability of wind power and the poor anti-interference ability are the main reasons causing the imbalance of wind power output and instability of wind power output. But the wind power generation, especially large-scale wind power integration, generally leads to the increase of grid load and some faults in other part of wind power generation.

5. Insufficient funds

Due to the large investment of wind power, the return time is relatively long, and the electricity price is set by the government, the electricity price is low, which leads to the wind power project income is too little, or even losses, and can only rely on national subsidies to barely maintain every year, so the lack of funds also restricts the development of wind power.

6. Insufficient safety performance of wind turbine

Although China began to focus more on the technology of wind power generation, the safety performance was not guaranteed well at the same time, even some equipment had much potential safety hazard. That not only can lead to the higher probability to fail, but also can increase the maintenance cost.

7. Imperfect industrial structure

The wind power industry started late in China, and there are not the formulated technical standards for that. Meanwhile, it makes the enterprises of wind power blindly follow the wind and compete according to the policy, which is a not good phenomenon.

8. Unstable quality of wind power products

In order to occupy the wind power market as much as possible, some enterprises compete fiercely in the production capacity, did not give enough on the testing period when they want to make a new product of wind power generation. Some products even are put into the mass production with less than one year testing, which has a great quality risk.

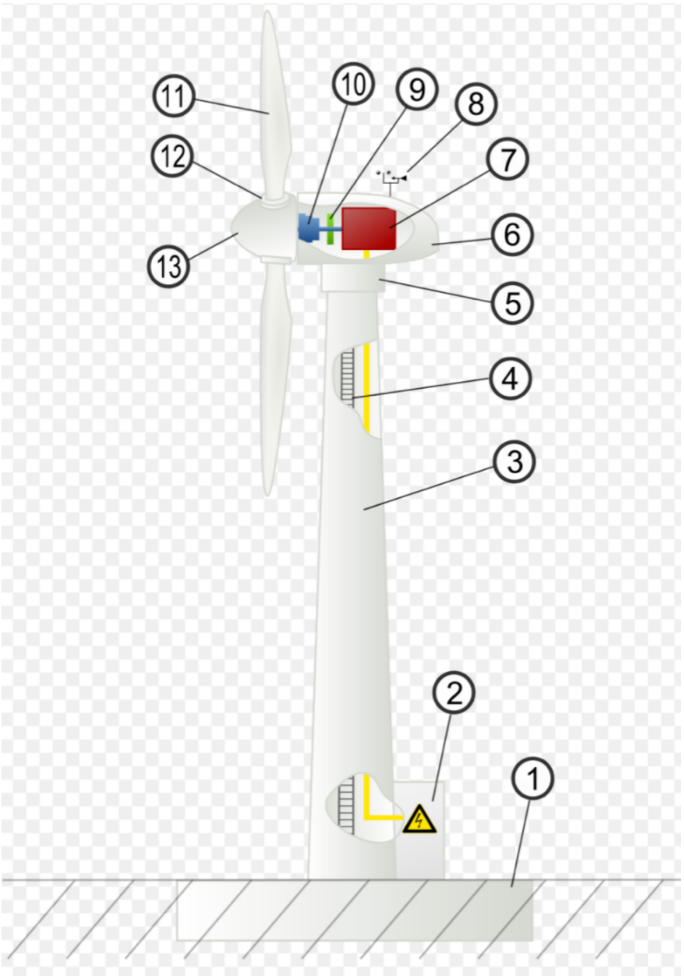
3.5. Analysis of wind farm of China in the future

Nowadays, the new energy is gradually accounting a big part of the energy demand of the world, Chinese governments also give much support to the wind power companies, but still weak at the supervisory system, and the governments also need give more money investment to solve the long period of return. At the same time, the problem of research and design is also settled. For the new products of wind power tower, it is important to give them enough experimental time, not only to pursue the speed because a small error can make a heavy safety accident.

In the future development of wind power, we should continue to optimize the development of wind power, strengthen the research and development of power storage technology, so that it can be widely used in wind power construction. At the same time, it is necessary to speed up the construction process of transmission power grid, and make a reasonable layout based on geographical factors and power grid distribution. We should also pay attention to the safety performance of wind power products, strengthen the detection and maintenance of existing wind power products, pay attention to the development and production of wind power products, and gradually replace the original batch of imported wind power products, to reduce the maintenance costs.

4. Basic components of wind turbines

The design of wind turbine is the process to define the form and configuration to extract the energy from wind. The wind turbine is the equipment that makes electricity, it captures the wind blowing through the wind wheel, the mechanical energy of rotation is converted into the electric energy. The main parts of the wind turbine are the wind wheel and generator, the improvement of power of wind turbine normally means the enlarged size of the wind wheel and generator[41].



1.Foundation;
2.Connection to the electric grid ;
3.Tower;
4.Access ladder;
5.Wind orientation control;
6.Nacelle;
7.Generator;
8.Anemometer;
9.Electric brake;
10.Gearbox;
11.Rotor blades;
12.Blade pitch control;
13.Rotor hub;

Figure 25. Components of wind power tower[41]

Rotor blade

The blade is the component of the wind wheel, it transfers the wind energy into the mechanical energy. A wind wheel normally has three wind blades, the angle between them is 120 degrees. The size of blades decides the power of a wind turbine. But the wind wheel will be stopped under the extreme wind or the emergency. The material of the wind blade is normally the glass fiber or high composite material. The shape of the blade is wing shaped and close to streamline.

Rotor hub

This component is the connecting part of the blades and the engine room, which transfer the mechanical energy from the wind wheel to the generator. It mainly bears the horizontal thrust, bending moment and torque. Normally, it is made of cast iron, the shape is mostly spherical, triangular or disc.

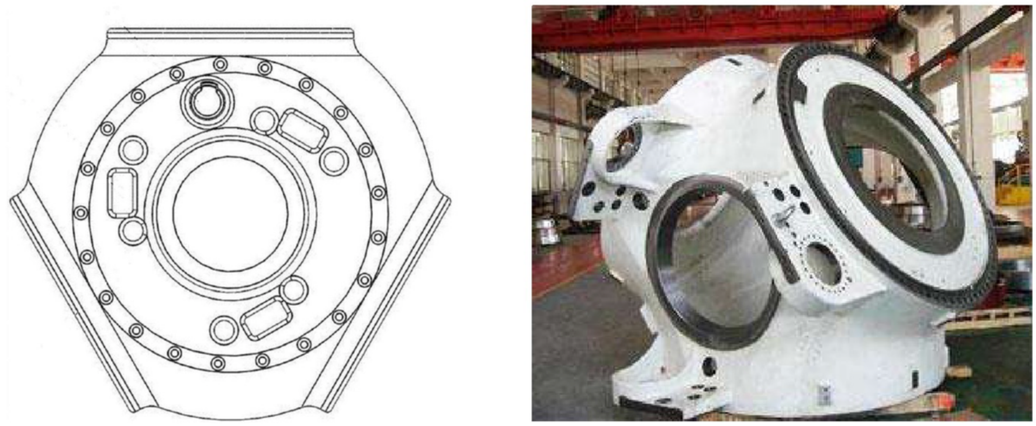


Figure 26. Rotor hub[42]

Engine room

The engine room is the control part and power generation part of the wind turbine, it generally contains all the mechanical and electrical components that transfer and convert the energy obtained by blades. It is at the top of the tower, can adjust according to the wind direction, also can stop the rotation of wind wheel. It is mostly the structure of cast iron, or welded by steel plate with ribs, and its shape is roughly a rectangle.

Structure of tower

According to the structure type, it can be divided into the cone tower and the truss tower. The cone tower is usually made of the steel, the section is a hollow circle, the diameter and the thickness of the circular ring increases from the bottom to the top. The tower is constructed piece by piece, uses the flange and bolts to connect each other. The truss tower mostly adopts concrete-filled steel tube structure, through the connection of concrete-filled steel tube web members and limb columns to form a support structure to support the upper fan. The force of the limb column is larger, with angle steel around, while the force of the inclined bar and cross bar is smaller. The structure has good passing rate, convenient construction, convenient for on-site installation and maintenance, but it is not conducive to the repair and replacement of the upper mechanical equipment.

Cone tower Truss tower

Figure 27. Structure of tower[42]

5. Failure of wind power tower

5.1. Failure type and rate

According to the paper of Ma and other scholars, wind turbines are designed and operated to interact with the environment to make the electricity including through extreme events. However, Human or mechanical errors and defects of constituent members and materials can still lead to lots of engineering accidents and structural collapse, where at least 6% have fatal consequences and about the half involve human injury. Therefore, it is a key question that we cannot ignore when making electricity energy. Most usual reasons of failure are the accidental load induced by typhoons or windstorms, fatal events concentrate at either early or late stage of the designed service life. Unexpected load conditions seemed to derive from defective blade positioning or braking which in turn over-stress areas of transition such as joints and openings. A large amount of wind turbine accidents is recorded each year, meanwhile, the rate of occurrence has increased over the last 20 years[43].

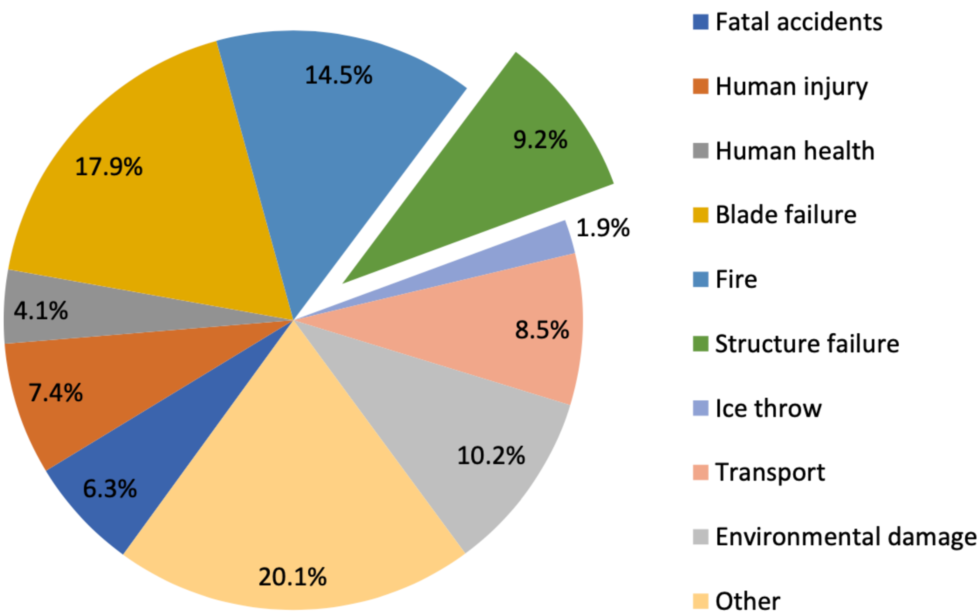


Figure 28. Failure type distribution of wind turbine incidents 1980-2016[43]

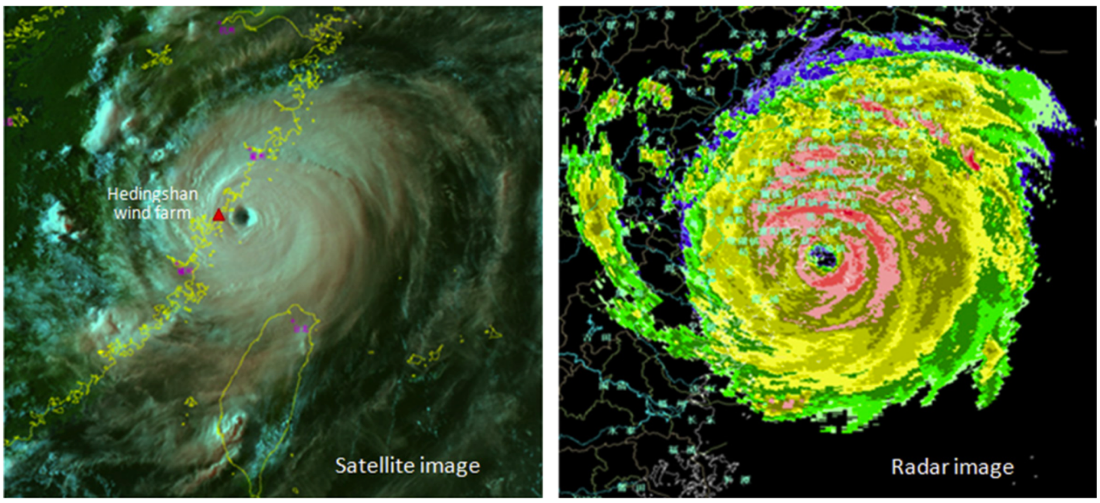


Figure 29. Satellite and radar images of super typhoon Saomai in 2006[45]

5.2. Latest failure cases in China

Although the technology of wind tower installation and testing is much higher than before, there are still some accidents[44]:

At about 10:37 on April 6, 2020, when the wind measuring tower of Huaneng Qinghai Gonghe 50000 KW wind power project was demolished to the fifth section of the wind measuring tower, the ground construction personnel collapsed suddenly in the process of loosening the South cable wind rope, resulting in the death of two operators in the fourth and fifth sections.

From 8:00 to 10:00 on May 4, 2020, one blade of a wind farm in Henan was broken, and the fracture was at the maximum chord length, while the other two were normal. When the accident happened, the average wind speed was 13.4 m/s, and the maximum wind speed was 25.89 m/s. The reason is that there are quality problems in the manufacturing of the equipment, such as cavitation, lack of glue, lack of stiffeners and other process quality defects in the web bonding during the blade clamping process, which cause web support failure and blade cracking deformation in the long-term operation process, resulting in insufficient structural strength of the blade.

On June 29, 2020, a crane boom of a Construction Engineering Co., Ltd. in Ningxia broke during the implementation of G30 tower sectional lifting and docking installation, resulting in one death and three injuries to the labor subcontractor.

At about 21:00 on July 4, 2020, the "Zhenjiang" occurred a seawater flooding accident during its operation in the Rudong sea area of Jiangsu Province. At present, the "Zhenjiang" is in the state of piling, and the equipment on board cannot operate normally. No casualties were caused in this accident. At present, the maritime department is still in the process of rescue.

5.3. Failure mode of wind turbines

Overall overturning

Under the action of typhoon, if the foundation structure form of fan is unreasonable, the foundation size or the buried depth are too small, it will be easily pulled out from the ground, then cause an overturning of the wind turbine.

Tower failure

It means that the stiffness of the tower is far less than that of the foundation, but the load at the bottom of the tower acts on the foundation. The bottom of the tower and the part without reinforcing ring are the most vulnerable parts of the tower in typhoon, which are prone to local yield or local buckling.

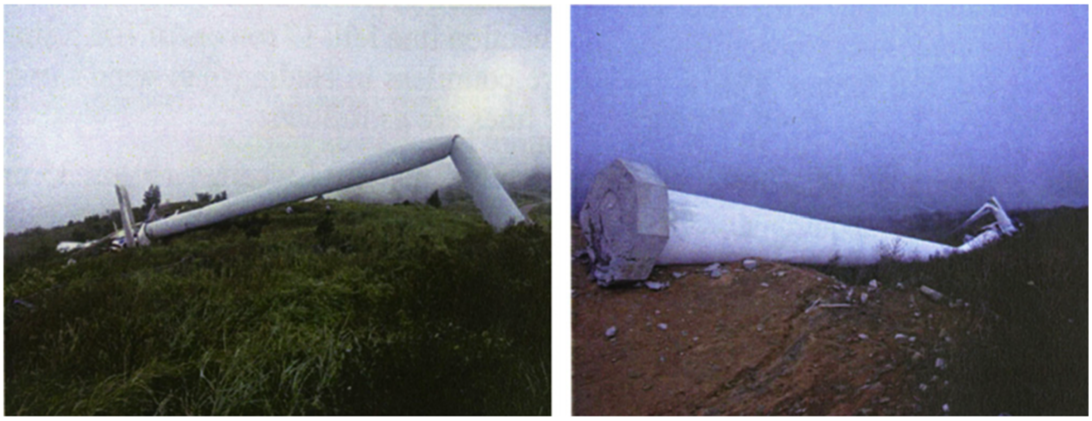


Figure 30. Tower collapse in super typhoon Saomai activity[45]

Blade failure

It means that the blade stiffness is far less than that of the foundation and tower, which is the most flexible component. Nowadays, the design shape of the blade is complex in order to capture more wind energy, means the failure mode will also differ between the different shapes of blades, but the root fracture and local bending shear torsion failure are the main ones.

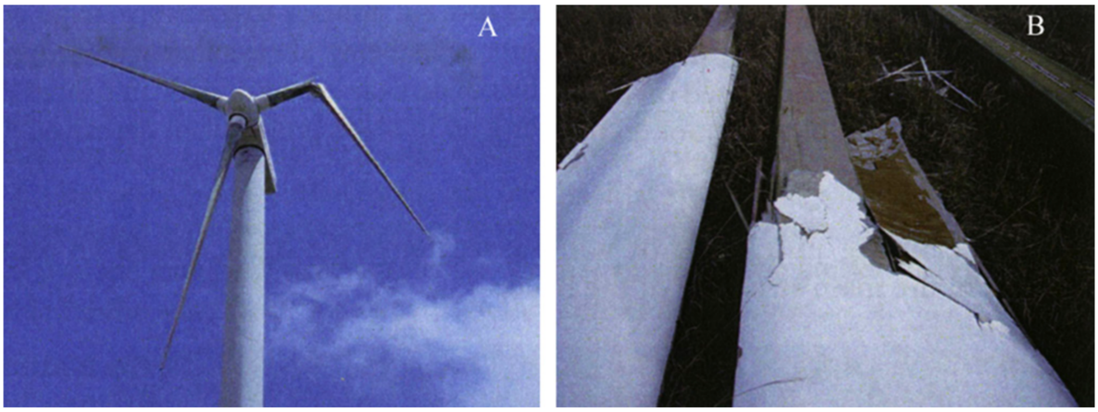


Figure 31. Blades damage in super typhoon Saomai activity[45]

5.4. Reason of the collapse of wind turbines

The collapse of wind power tower under extreme wind conditions is commonly due to insufficient bearing and buckling strength. The buckling strength is the most demanding requirement of tower design due to the uneven thicknesses. However weak points on walls appears on the thickness changing zones of tower wall, door opening areas, and connection areas. In the past cases, the local buckling across tower shells could have led to total loss of wind turbines triggered by a domino-like effect. On the other hand, although the entire wind turbine can be regarded as a stationary structure, aeroelastic effects stand up as a major risk. This is demonstrated by the recurrent failure of rotor blades, because the recorded tower collapse cases did not only fracture when the design wind speed was exceeded but also under lower wind speed level condition.

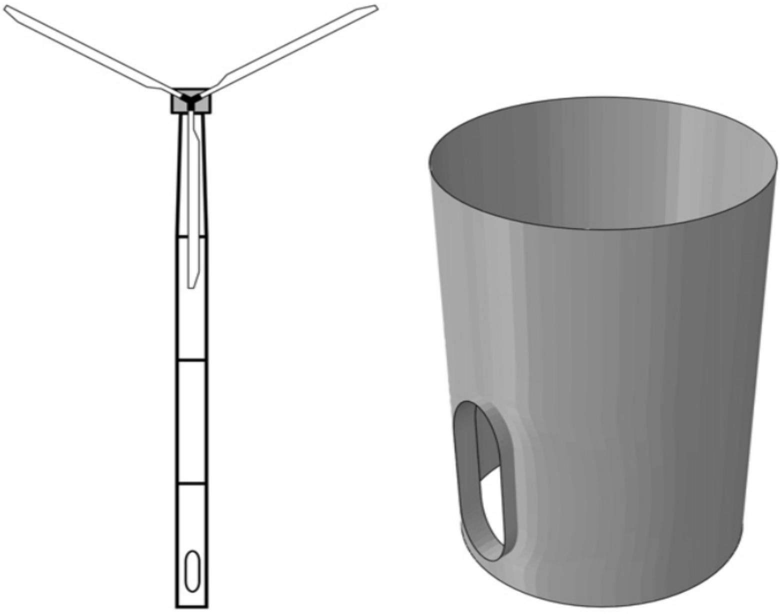


Figure 32. Door opening of wind tower[46]

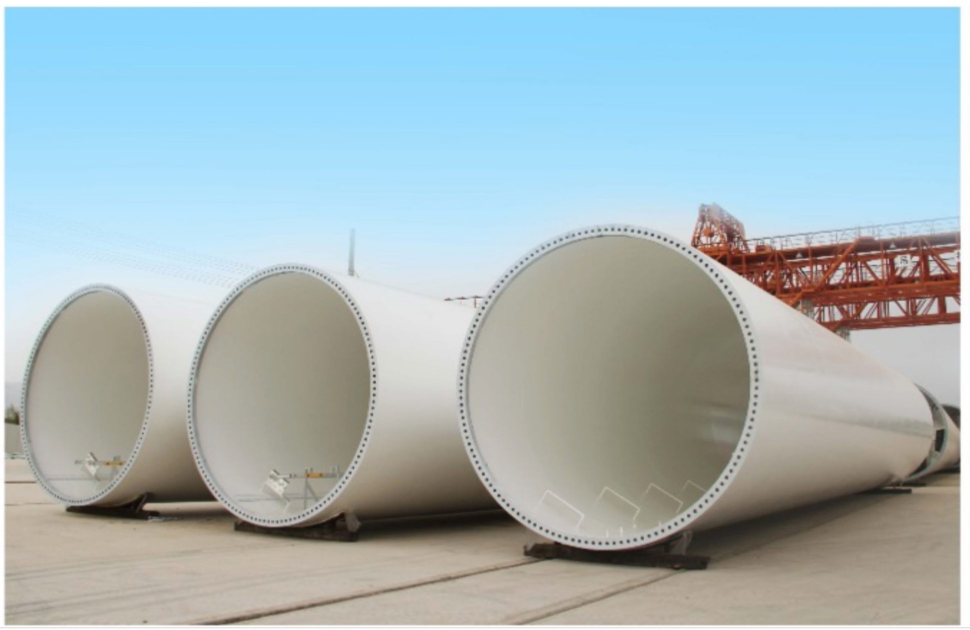


Figure 33. Connection areas of wind tower[47]

6. Numerical analysis

6.1. Application case

As commonly used structure type, the cone tower is the prototype analyzed here:

Name	Property
Shape of cross section:	Hollow cylinder
Diameter of cross section:	Decrease from bottom to top
Thickness of tower:	Decrease from bottom to top
Material:	Alloy steel (Q345B\Q345C\Q345D\Q345E)
Tower pieces:	Homogeneous material
Connection:	Using flanges to connect tower pieces
Main loads to bear:	Wind load, seismic load, self-weight, weight of top structure
Other parts of tower:	Gate on the bottom, equipment inside

Table 6. Information about the cone tower

The wind turbine is built in Chongming District of Shanghai. The total height of the tower is 63.150 m, the bottom diameter of the tower is 4.035 m, and the top diameter is 2.955 m, the bottom wall thickness is 80 mm, and the top wall thickness is 65 mm. The radius of wind wheel is 35.000 m, the total weight of the tower structure is 91.000 t, the total mass of blade and hub is 26.886 t, the total weight of engine room is 60.000 t. The whole structure of our example is made of Q345C, the modulus of elasticity is 210 GPA, Poisson's ratio is 0.3, and the density is 7850 kg/m^3. The construction site of the wind power tower is Shanghai, the seismic precautionary intensity is 7 degrees, and the characteristic period of the site is 0.4 s. The engine room is simplified as a steel block with the dimension 4m*3m*2m[48].

The seismic precautionary intensity and the characteristic period are the defined parameters of a region in the Chinese code for the seismic design. Both just depend on where the structure is built.

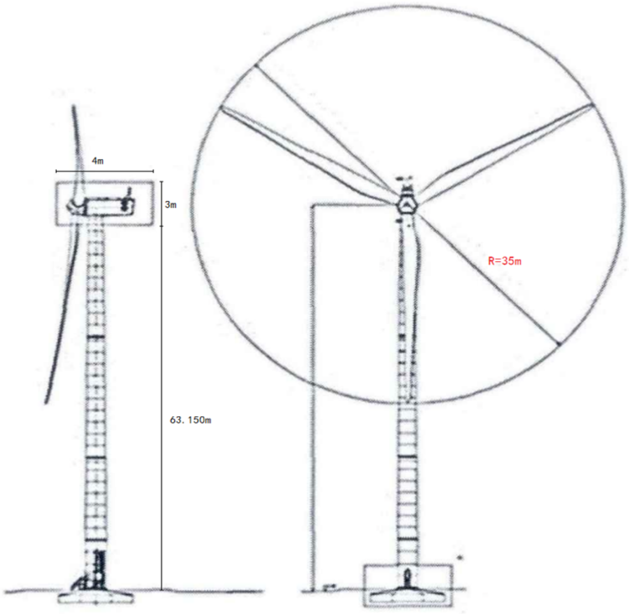


Figure 34. Wind tower structure

Take the maximum wind speed 25 m/s on the wind hub, ignore the influence of the wind load on the tower part of our structure because the wind force on the tower is much smaller than the wind force from the blade, ignore the influence of the door opening and the connection of the tower. The tower can be regard as a cantilever beam, use the beam theory and the equivalent static force to do a finite element analysis in MATLAB. Check where the maximum stress concentrates, whether the stress meets the requirement of the design strength of the Chinese code, the value of the maximum displacement of the tower.

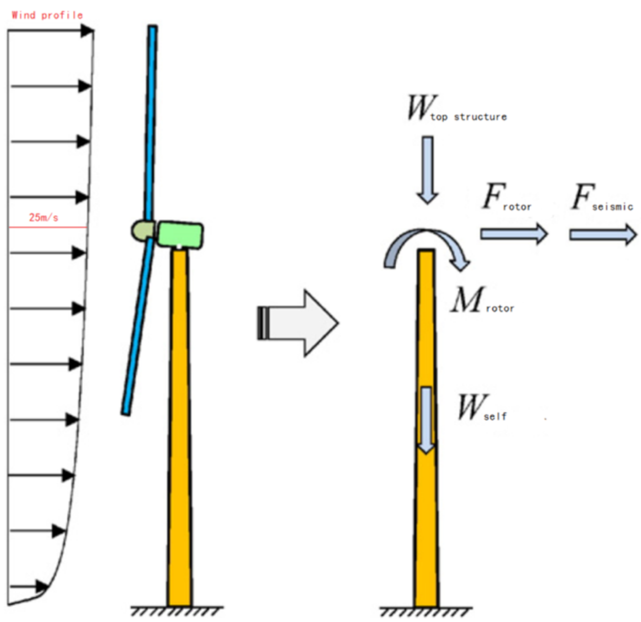


Figure 35. Simplified structure

Due to the influence of vegetation and buildings near the ground, the wind speed will increase along the height. One past paper proved that the relationship between wind speed and height near the ground basically satisfies the following equation[49]:

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^n$$

v : wind speed at the height H.
H_0: reference height (normally take 10m as the reference).
v_0: wind speed at H_0.
n: roughness coefficient of the ground.

Ground type	Roughness coefficient
Smooth (water, sand, snow)	0.10～0.13
Slightly rough (grass, crops, rural areas)	0.13～0.20
Rough (woods, suburbs)	0.20～0.27
Very rough (city, tall building)	0.27～0.40

Table 7. Roughness coefficient

6.2. Load calculation

According to the Chinese code for design of high-rise structure (GB50135-2019), the loads on high-rise structures can be mainly divided into three kinds:

Permanent load: self-weight of structure, weight of fixed equipment, weight of soil in materials, earth pressure, tension of rope, internal prestress of structure, deformation of foundation, etc.

Variable load: wind load, seismic load, mechanical load, dynamic action of mechanical equipment, icing load, snow load, installation and maintenance load, etc.

Accidental action: impact, explosion, rare earthquake action, etc.

Here, we consider the self-weight of the structure, wind load and seismic load as the main loads. Ignore mechanical load, snow load, installation and maintenance load, etc.

6.2.1. Weight of top structure

$$W = m \cdot g$$

m: total mass of wind blade, wind hub and engine room.

g: acceleration of gravity, $9.8\ m/s^2$.

Finally, got $W = 851483\ N$.

6.2.2. Wind load on the blade

According to the Saint Venant principle, the horizontal concentrated force has little effect on the performance of the whole tower structure of wind turbine. The horizontal concentrated force exerted on the fan head after the wind load is applied to the wind turbine can be calculated by the following formula[13]:

$$F = C_p \cdot v^2 \cdot S$$

C_p: coefficient of wind power use, normally equals 0.4.

v: speed of wind, normally 8~25 m/s on the wind hub because when it exceeds 25m/s, the wind turbine will shut down in an emergency.

S: swept area of the wind wheel, (962 m^2 for the 35m-radius wind wheel) .

In the design of high-power horizontal axis wind turbine, ignore the speed gradient of wind speed in the range of vertical height equal to the diameter of wind wheel, and the speed at the center of the wind turbine can be used as the design wind speed[49]. Here, consider the average speed 25 m/s on the wind blade area for our design. Finally, got $F_w = 240468\ N$.

6.2.3. Moment from the rotor

The moment is moment caused by the gradient wind speed on area of the wind wheel[16]:

$$M = \frac{8}{27}\frac{\rho}{3}\pi r^2({v_1}^2 - {v_2}^2)$$

ρ: density of air at standard atmospheric pressure, 1.29 kg/m^3.

r: radius of wind wheel.

v_1: wind speed at the top of wind wheel.

v_2: wind speed at the bottom of wind wheel.

From the governing equation of wind profile, got $v_1 = 26.5842\ m/s$, $v_2 = 22.3803\ m/s$. Then $M_w = 100927\ N \cdot m$.

6.2.4. Seismic load

There are three methods to calculate the earthquake effect: base shear method, response spectrum method, time history analysis method. The response spectrum of the considered structure is evaluated here according to the Chinese code for seismic design of buildings (GB50011-2010).

Maximum value of horizontal seismic influence coefficient: $\alpha_{\max} = 0.08$.

Characteristic period of site: $T_g = 0.4\ s$.

Damping ratio of structure: $\zeta = 0.05$.

Attenuation index of descending section of response spectrum: $\gamma = 0.9 + \frac{0.05-\zeta}{0.3+6\zeta}$.

Slope adjustment factor of straight-line descending section of response spectrum: $\eta_1 = 0.02 + \frac{0.05-\zeta}{4+32\zeta}$.

Damping adjustment factor of response spectrum: $\eta_2 = 1 + \frac{0.05-\zeta}{0.08+1.6\zeta}$.

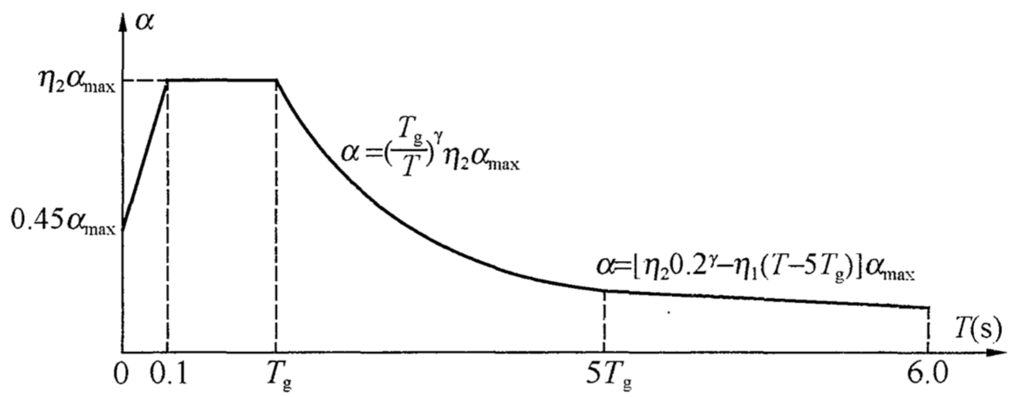


Figure 36. Curve of seismic influence coefficient

The response spectrum (the curve of seismic influence coefficient) is the relationship between the seismic influence coefficient α and the neutral period of vibration.

From the neutral period of vibration of the structure, easy to get the value of seismic influence coefficient α. The seismic load:

$$F = \alpha \cdot m \cdot g$$

g: acceleration of gravity, $9.8\ m/s^2$.

m: the total mass of wind turbine.

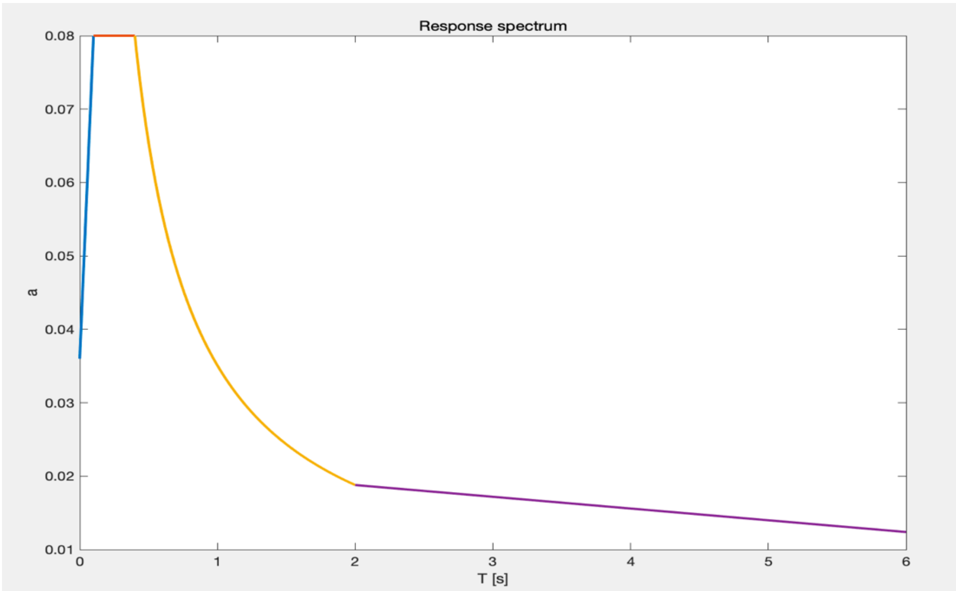


Figure 37. Response spectrum for the structure

Neutral period of vibration of our structure is defined by the formula:

$$T = 0.0277 \cdot m^{0.129} \cdot H^{0.709}$$

Here, m is the total mass of wind turbine, H is the total height of wind tower. Then $\mathrm{T} = 2.5734\ s$. Easy to get the value $\alpha = 0.0179$ from the response spectrum of our structure, then $F_s = 31164\ N$.

All the forces calculated above are applied at the top of the wind tower using a MATLAB script to evaluate the resulting displacements.

6.3. Model construction

As we know, the finite element model is a good method to analyze the structural response and displacement. The tower part of wind turbine is simplified as a cantilever beam, the structure is discretized along the height, take the middle cross section as the cross-section geometry of each mesh because of the increasing diameter and thickness.

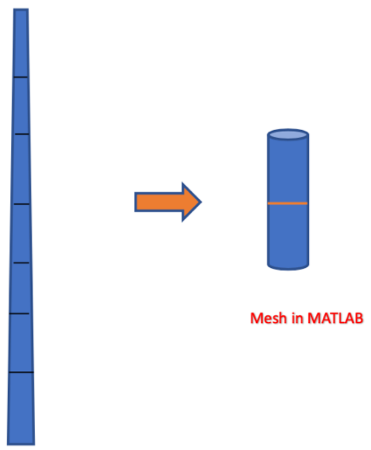


Figure 38. Definition of mesh in MATLAB

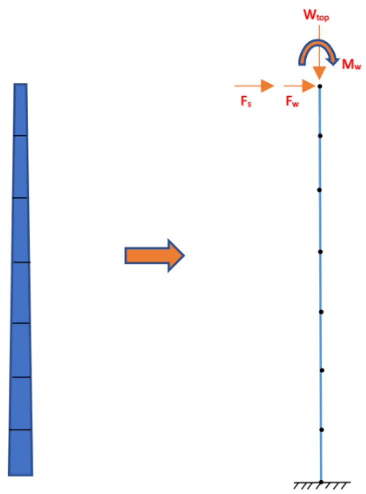


Figure 39. Model construction in MATLAB

6.4. Rough mesh

Number of nodes: 8, number of elements: 7.

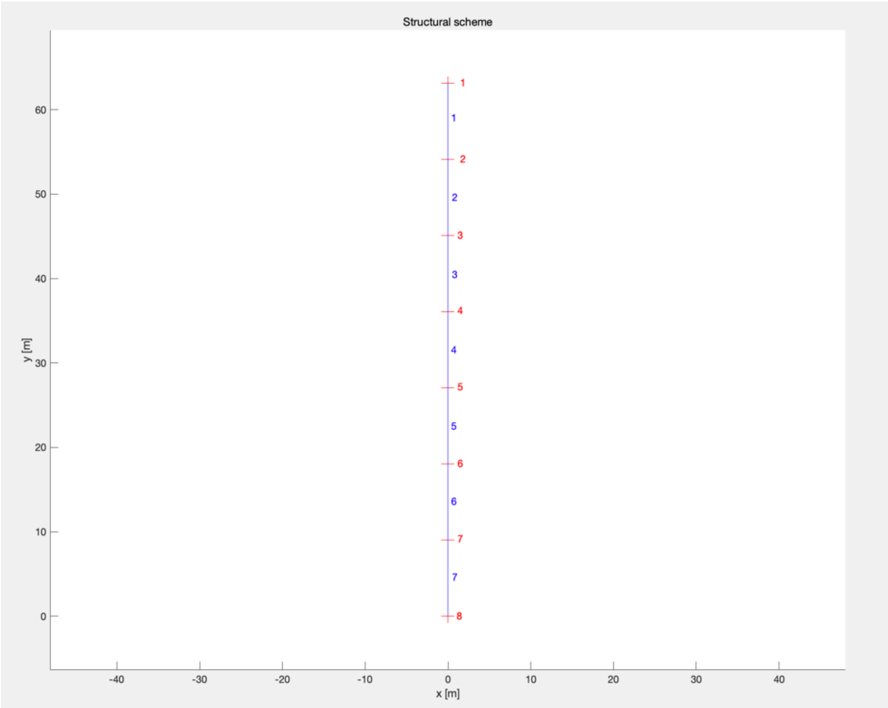


Figure 40. Structure scheme

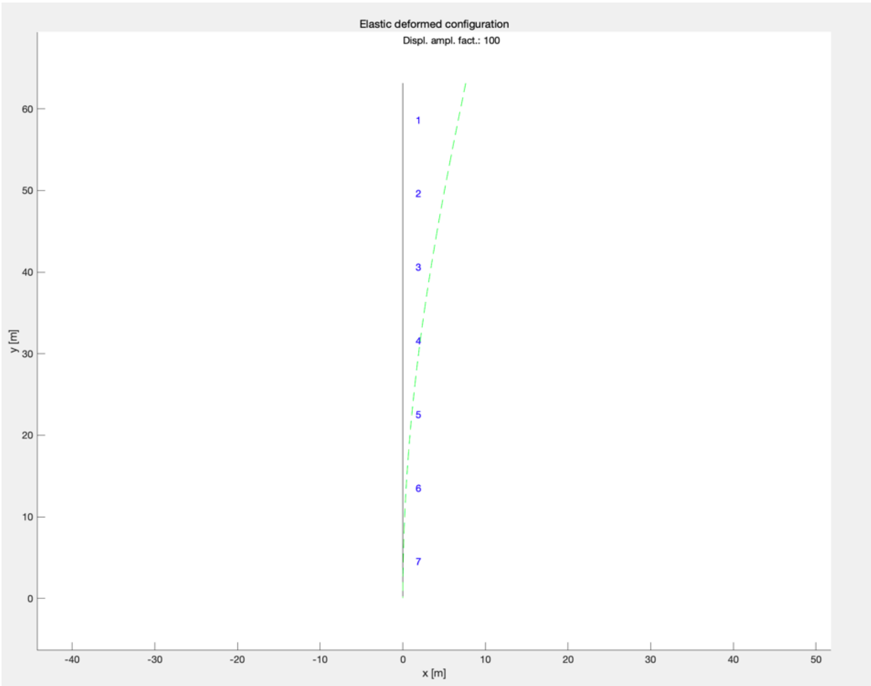


Figure 41. Deformed configuration

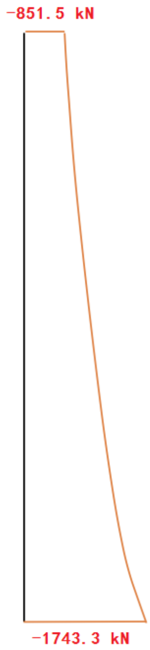


Figure 42. Axial force distribution

Figure 43. Shear force distribution

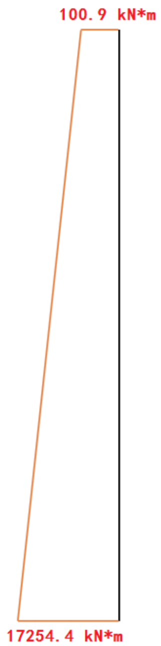


Figure 44. Bending moment distribution

The internal force diagrams are recovered by the force method, the axial force increases by a cubic relationship because of the increasing diameter and the increasing thickness, the shear force does not change along the height, the bending moment increases linearly.

6.4.1. Stress

Due to the bending moment, the normal stress distributes linearly from left to right, it has the maximum value at the right end. The maximum shear stress still occurs at the middle area of the cross section, the value is uniform, and the direction is parallel to the shear force. The stresses:

Normal stress: $\sigma_y = \frac{N}{A} - \frac{M}{W_z}$.

Maximum shear stress for the hollow circle cross section:

$$\tau_{xy} = \frac{VS_z}{Ib} = \frac{4V}{3A}\left(\frac{R^2 + R \cdot r + r^2}{R^2 + r^2}\right)$$

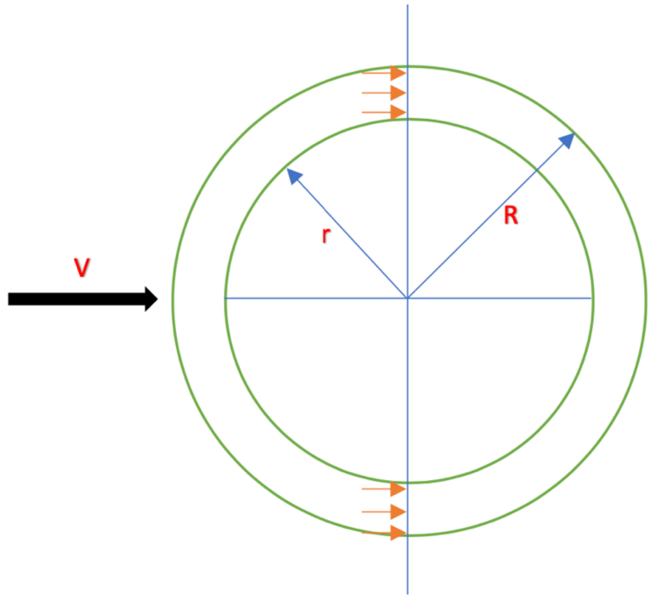


Figure 45. Maximum shear stress distribution

Position	Normal [MPa]	Shear [MPa]
top	-1.69	0.92
bottom	-19.67	0.55

The marked number in red color in the table is the maximum values of the stresses. The maximus normal stress appears at the bottom of the tower, the maximus shear stress appears at the top of the tower.

According to the Chinese code for design, manufacture and erection of steel tubular tower of wind turbine (NB/T 10216-2019) for Q345C (wall thickness from 65 to 80mm), the design value of tensile, compressive, flexural strength f=280 MPa, the design value of shear strength f_v=160 MPa.

6.4.2. Displacement

From the beam modal defined, clear to know that the maximum displacement will appear at the top of tower. The displacements returned by MATLAB are:

Horizontal [mm]	Vertical [mm]	Rotational [rad]
76	0	-0.0020

At present, there are no standard restrictions for the maximum displacement of the wind tower. According to [50], the practical requirement to ensure the normal operation of the wind turbine, suggests that the allowable horizontal displacement of the tower is within the limit of 0.8% of the height of the tower. The height of the wind tower is 63.150 m, the maximum allowable displacement is therefore 505 mm (much bigger than 76 mm).

6.5. Fine mesh

The displacement values are verified by means of a finer mesh, made of 15 nodes and 14 elements. The internal force diagrams and stresses do not change with the model.

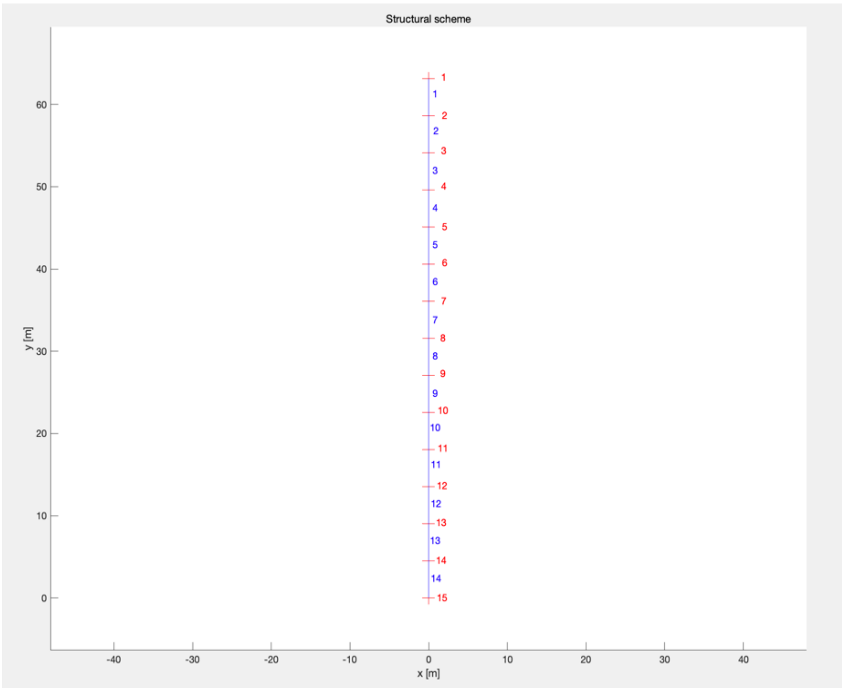


Figure 46. Structure scheme

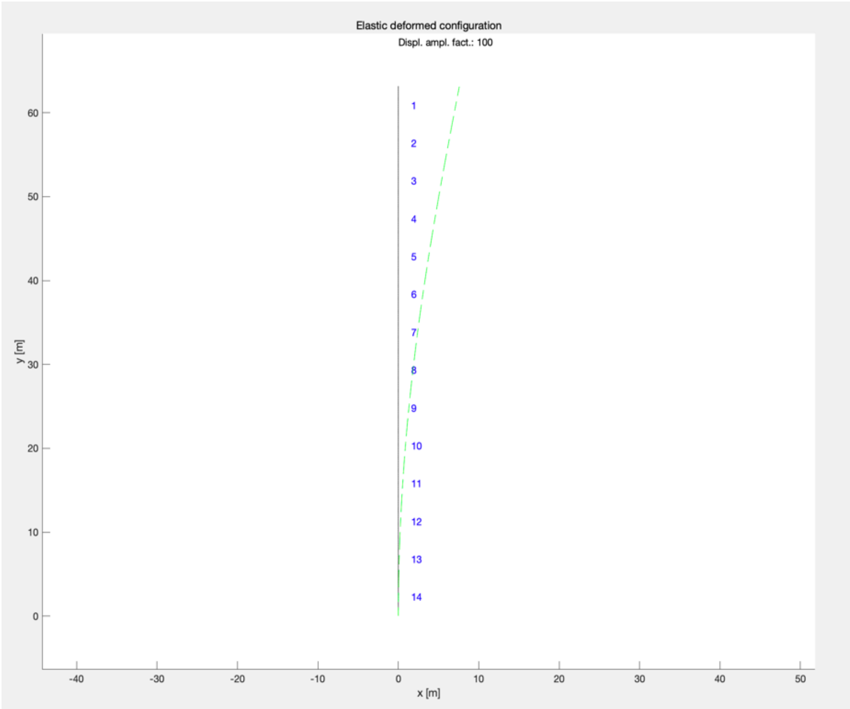


Figure 47. Deformed configuration

The maximum horizontal displacement does not change.

7. Summary and conclusion

With the rapid development of the wind power industry, the analysis for the wind power tower is also increasing. The onshore wind power towers are simply built on land, such as fields, tops of mountains or even the backyard of houses. They need lower installation cost and lower maintenance cost, and are also preferred by many entrepreneurs because of the faster investment payback. To properly build an onshore wind farm, the study of the terrain and wind currents must be performed. The offshore wind power towers are built over the sea and far from the coast, they have higher potential for the power generation due to the faster and more stable winds on over the sea, and there is no noise pollution. Offshore wind farms also enjoy a less troublesome inconsistency because of the constant wind with higher speeds.

According to the structure type, the structure of wind power tower can be divided into two kinds: the cone tower and the truss tower. The cone tower is usually made of steel, use a hollow circular ring cross section, the diameter and the thickness of the cross section increases from the bottom to top. The truss structure mostly adopts concrete-filled steel tube structure, through the connection of concrete-filled steel tube web members and limb columns to form a support structure for the upper fan. Nowadays, the cone tower is commonly used for the wind farm construction, which is also the structure type analyzed in the thesis.

Based the statistical data, the failure of the wind turbine has many reasons, such as fire, structure failure, ice throw, transport. This thesis work focuses on the structural analysis of a simplified model of a wind power tower. Ignoring the influence of the wind load on the tower part of the structure and the presence of the opening and connection, the upper part structure with the wind turbine is simplified as a mass point, and the wind tower is simplified into a cantilever beam. All the forces are applied at the top of the wind tower. The performed computations show that: the maximum evaluated stresses satisfy the prescription of the Chinese code, the maximum horizontal displacement is consistent with the heavy simplifications introduced with the performed preliminary analysis that neglects the critical details of the structure.

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