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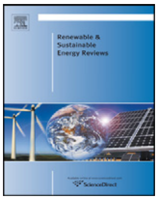

Wind energy development and its environmental impact: A review

Dennis Y.C. Leung*, Yuan Yang

Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

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ABSTRACT

Wind energy, commonly recognized to be a clean and environmentally friendly renewable energy resource that can reduce our dependency on fossil fuels, has developed rapidly in recent years. Its mature technology and comparatively low cost make it promising as an important primary energy source in the future. However, there are potential environmental impacts due to the installation and operation of the wind turbines that cannot be ignored. This paper aims to provide an overview of world wind energy scenarios, the current status of wind turbine development, development trends of offshore wind farms, and the environmental and climatic impact of wind farms. The wake effect of wind turbines and modeling studies regarding this effect are also reviewed.

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* Corresponding author. Tel.: +852 2859 7911; fax: +852 2858 5415.
E-mail address: ycleung@hku.hk (D.Y.C. Leung).

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1. Introduction

Rapid global economic growth has contributed to today's quickly increasing demand for energy. However, conventional fossil fuels such as coal, oil and natural gas, which have been a key energy source since the industrial revolution, are not only facing depletion, but has also gradually become a source for concern regarding its serious adverse effects on our environment. Hence, the quest to develop renewable and clean energy sources, such as solar, wind and solar-hydrogen energy, is imperative and timely [1]. Among these many renewable resources, wind power is the only one that offers a mature technique, as well as promising commercial prospects, and is now generally applied in large-scale electricity generation [2].

Wind power has a history more than 3000 years old, and people began to use it to generate electrical power about 120 years ago. The development of wind power has always fluctuated with oil prices. The technology of wind power was first boosted during the 1970s oil crisis, but damped down afterwards [3]. During the last decade, due to the concessionary policy towards the wind power industry adopted by many countries, the wind market has developed rapidly, and the wind turbine technology has experienced an important evolution over time. Beyond the original pioneering countries, such as Germany, the USA, Denmark and Spain, countries like China and Turkey have made substantial efforts to develop their wind power industry [1,3,4]. It is predicted that wind energy will provide 5% of the world's energy in 2020 [5]. However, the wind energy that use today mostly comes from onshore winds. Meanwhile, there is a growing interest in offshore wind, as the wind is normally stronger and more uniform at sea than on land. European countries are the leaders in offshore wind, and Denmark has been applying offshore wind to supply electricity for about 20 years [6]. In countries like the US, where coastal wind sources are abundant, offshore wind has the potential to become a major energy source for domestic applications [7].

Though wind power has performed well in recent years, it also creates a strong environmental impact, such as noise, visual and climatic impact. Although these impacts seem minor when compared with fossil fuels, its effect on humans should not be overlooked, due to its potential great development in usage. It is necessary to figure these potential drawbacks out, especially their potential long-term effects, and to find solutions to them in order to retain the long-term sustainability of wind energy.

This paper aims to provide an overview of the world wind energy scenario, current development of wind turbines, the development trend of offshore wind power, and the environmental and climatic impact of wind on humans. It also introduces various numerical simulations for wind studies, which is of value to mention, as these simulations are commonly used in the design and assessment of wind turbines, and may be more useful in solving problems than experiments or field measurements.

2. Historical background

Humans have a long history of using wind energy; they have employed wind power for much longer than the application of coal and refined petroleum. In Egypt, about 3000 years ago, people began to use windmills to pump water. Furthermore, Chinese farmers started to use wind wheels with a vertical axis of rotation to drain rice fields, centuries before Europeans did so. However, the horizontal axis windmill was probably invented in Europe, and was first found in the year 1180 in the Duchy of Normandy [8].

People began to use windmills to generate electricity from the time when Prof. James Blyth, in Scotland, first built a windmill to generate electricity in 1887 [9]. Meanwhile, in the year 1888, the wind machine developed by Bruch and his colleagues was successfully put into operation on the Atlantic coast. From this moment forward, wind power technology began to develop step by step [10]. In 1920, Kurt Bilau applied the Ventikanten blade, using an aircraft airfoil that he and Betz developed, in a modern windmill design [8]. During the 1920s and 1930s, America widely developed small wind machines (<1 kW) and windmills without electrical systems in its rural places. During this period the popularity of windmills used reached its highest levels in the US, with about 600,000 units installed [1,11].

In 1941, a prototype of the modern horizontal axis wind turbine was built in the US, and wind turbines were widely used to provide electricity to farms to which electric power lines could not reach [1,12]. However, with the widespread development of electric power lines, the wind turbine market was gradually diminished, beginning in the 1950s [1].

When examining the development history of wind power, it is clear that the popularity of wind energy has always fluctuated with the price of fossil fuels. Since the oil crisis in the early 1970s, the price of oil skyrocketed, which led to a focus on wind power development, and a boom took place in 1995 [13]. In the last decade, wind power experienced a leap in usage; since the beginning of the 21st century, the world wind electricity-generation capacity has doubled approximately every three and a half years [13,14].

Table 1
Installed (2010) and proposed installed (2020) capacity (MW) in the current top five countries.

Country	Total installed capacity	Proposed installed capacity	Ref.
China	42,287	200,000	[17]
US	40,180		[18]
Germany	27,214	55,000	[20]
Spain	20,676	45,000	[22]
India	13,065		[23]

3. Current status of world wind energy

Over the last decade, the world's wind power generation capacity has been growing rapidly, with an average annual growth of about 30%. Fig. 1 shows the global wind power capacity installed between 1990 and 2015 (estimated for the installed capacities from 2010 to 2015). It indicates that at the end of 2009, the world wind energy's installed capacity reached 158 GW, a 31% increase over 2008. According to the data published by the World Energy Association, at the end of the first half of 2010, the installed capacity reached 175 GW, and it is estimated that the capacity will hit 292 GW by 2012 and 425 GW by 2015 [15,16].

3.1. Installed wind power capacity in selected countries

The updated top five market contributors of the global installed wind energy capacity are China, the US, Germany, Spain and India, respectively. The following section will give a brief overview of wind power installed capacity and outlook in these five leading countries, as well as some representative European countries. Table 1 shows the installed capacity data of the five leading wind power countries between 2001 and 2010, while Fig. 2 clearly demonstrates their development trends and speeds over the past decade.

3.1.1. China

In 2010, China overtook the place of the US as the leading producer of wind power, hitting a total of 42.3 GW, adding 16.5 GW over the year, a 64% increase over 2009 [17]. It is not surprising

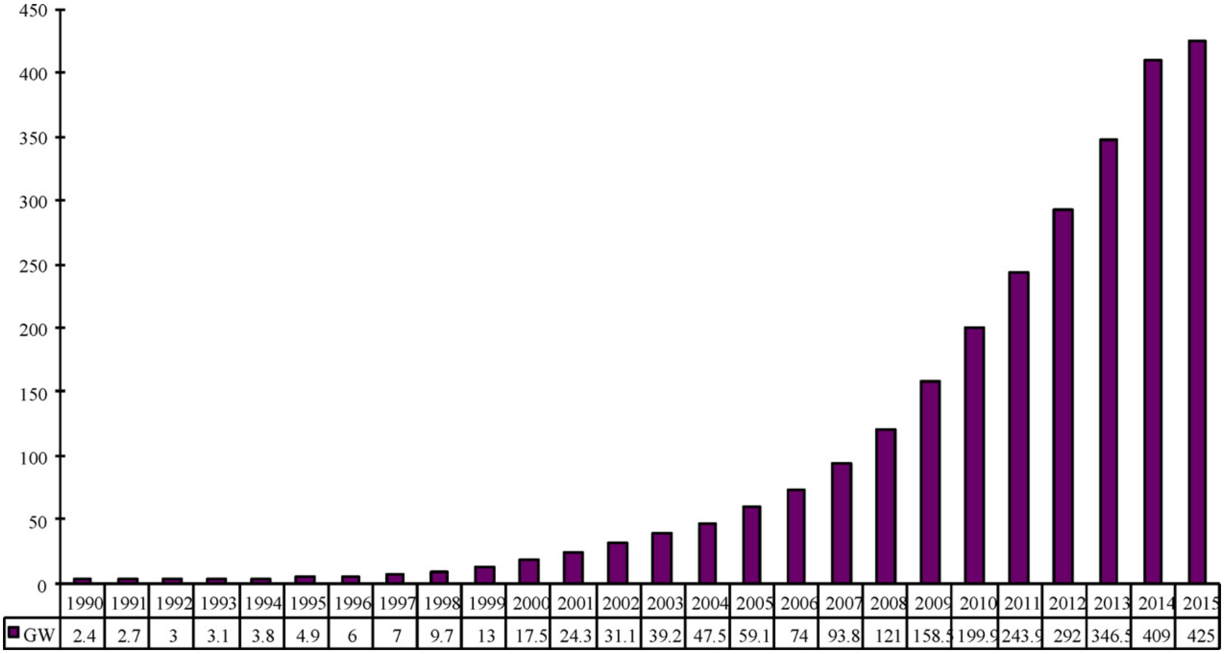

Fig. 1. Global wind power installed capacity, GW, 1990–2015 [30].

that China replaced the United States as the biggest wind market, because China's total installed capacity has doubled every year from 2006 until today, as shown in Fig. 2. Besides, the source of wind energy is abundant in China, second to the capacity of the US. The total exploitable capacity of China for both onshore and offshore wind energy is around 700–1200 GW, according to the third National Wind Energy Resources Census [4].

China began to utilize wind power in the 1970s. However, its use of wind power developed slowly until 2006, when "The Renewable Energy Law of China" was issued. China's wind power market then experienced a breakthrough, and its total installed capacity reached 12 GW at the end of 2008, an increase of 8.6 times over its capacity in 2005.

With its rapid and seemingly unhampered expansion, the next goal of the Chinese wind power market is to reach 90 GW by 2015 and 200 GW by 2020, in which year China also plans to build an independent technical system [17]. It is hoped that wind power will also play a major part in China's energy structure in the middle of this century [4].

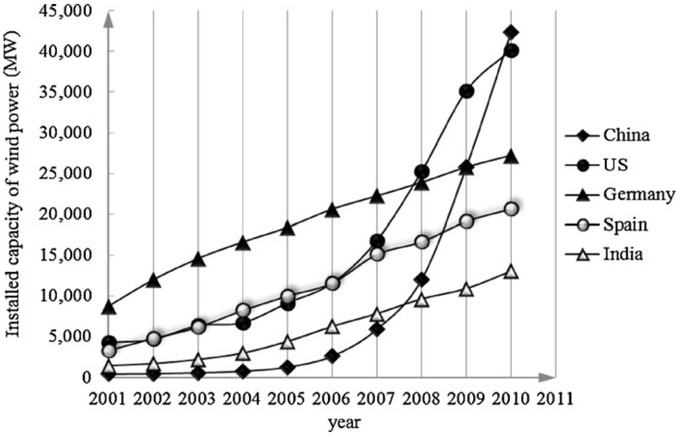

Fig. 2. Installed capacity of wind power in current top five countries (data, Refs. [17,18,20,22,23]).

3.1.2. The United States

Although the United States' wind energy capacity was surpassed by that of China in 2010, up to 5.1 GW were installed in the USA in 2011, making the total installed capacity 40.2 GW [18].

The USA lacks certain policies to support the development of renewable energy, which makes the US wind industry fall into the up-down cycle mentioned previously. 2009 was a record year for the US wind industry; with the support of the federal tax policies, its total installed amount reached 35.2 GW, with more than 10 GW installed in one year. Despite the fact that the growth slowed down in 2010, the 1.2 GW of wind power newly installed in the first half of the year can still generate enough power for 9.7 million homes [19].

It is estimated that by 2030, wind energy will generate 20% of the US electricity if there are proper US policies, while at present it provides around 2% of the nation's electricity. The future of wind power in the US seems uncertain, but the manufacturers are appearing to treat the slowdown in 2010 as a short-term phenomenon [18].

3.1.3. Germany and Spain

Germany and Spain are the first two leading wind power producers in Europe; in the past decade they have maintained a steady rate of development in the wind industry.

With 1.5 GW of installed capacity added in 2010, Germany's installed wind capacity reached 27.2 GW, providing 6.2% of the nation's electricity, which enabled it to maintain its leading place in Europe wind power [20]. What's more, the new installed capacity includes 108 MW of offshore wind power. On the other hand, the rapid development of wind power has also created 5000 jobs for around 100,000 people [21]. It is predicted by the German Wind Energy Association that the country would hit 45 GW of onshore and 10 GW of offshore wind by 2020 [20].

Despite experiencing a financial crisis in 2010, Spain still retained its second place in Europe, after Germany, by adding 1.5 GW, bringing the total installations up to 20.7 GW [22]. On windy days, wind power can be the largest energy source in the country, and 2010 was a special, particularly windy year, so that wind power accounted for 16.6% of the national net power consumption [22].

Table 2
Top 10 largest onshore wind farms until 2010 [31].

Rank	Wind farm name	Capacity (MW)	Country	Start-up year
1	Roscoe Wind Farm	781.5	USA	2008
2	Horse Hollow Wind Energy Center	735.5	USA	2005
3	Capricorn Ridge Wind Farm	662.5	USA	2007
4	Fowler Ridge Wind Farm	599.8	USA	2009
5	Sweetwater Wind Farm	585.3	USA	2003
6	Buffalo Gap Wind Farm	523.3	USA	2005
7	Dabancheng Wind Farm	500	China	1989
8	Meadow Lake Wind Farm	500	USA	2009
9	Panther Creek Wind Farm	458	USA	2009
10	Biglow Canyon Wind Farm	450	USA	2007

It is predicted by the Spanish Wind Power Association and the Renewable Association that Spain should reach a capacity of 45 GW (40 GW on-shore and 5 GW offshore) by 2020. However, it will be crucial to achieve this goal in 2011 because of the country's financial problems [22].

3.1.4. India

By supporting renewable energy policies in 2003, India achieved great energy returns in 2010 by adding new wind energy installations of 2.1 GW, reaching a total of 13.1 GW at the end of 2010; this put India in fifth place as a global producer of wind power [23].

3.1.5. Other potential European wind producers

2010 was also a record year for wind power production in European Union countries; 9.9 GW of wind power were installed across Europe, with European Union countries accounting for 9.3 GW of the total. Except for Spain and Germany, France was the biggest contributor (1.1 GW), followed by the UK (1 GW) and Italy (0.8 GW) [24].

Wind power potential is well distributed in France, and it is the second biggest producer of wind power in Europe. Since 2007, France has an added amount of wind capacity of around 1 GW every year and in 2010, French wind energy capacity reached 5.7 GW [25]. The long-term target set by the French government is to reach 25 GW by 2020, including 6 GW from offshore winds. However, whether or not the 2020 target can be met is largely decided by French legislation and regulations towards wind power [25].

For the UK, the total installed capacity of wind power topped 5 GW in 2010, and offshore wind broke the 1 GW barrier [26]. 71 onshore wind farms were approved by the British government this year, and the 33 wind projects under construction, offering a total capacity of 1.1 GW, marked another milestone in the UK wind industry [27]. Furthermore, offshore wind power in the UK has been developing rapidly; it is on track to hit 1.3 GW at the end of 2010, and there are still 3 GW of projects waiting to be built up to 2014 [27]. Offshore wind is expected to have a good future, as it provides a greater possibility of using different types of wind turbines and faster rotating blades, without considering noise and visual hazards.

3.2. Wind turbine size

Nowadays, in order to capture more wind power and to bring down the cost of renewable energy generation, more powerful and larger-scale wind turbines are needed. Therefore, the sizes of the wind turbines, including both blade length and generation capacity, are becoming larger and larger.

In a large modern wind turbine, the generator can be 100 times of the size of a similar turbine in 1980, and the blade length has increased almost 8 times over the same period [28]. Typically, the rotor diameter in modern wind turbines ranges from 40 to 90 m, and is rated between 500 kW and 2 MW [29]. Until now, the maximum onshore turbine size in operation is 6.5 MW, which doubled the size of the largest turbine in 2005 [30]. A 7.5 MW turbine is in Clipper's 2012 plan, while both Clipper and Sway are on the way to developing a 10 MW one [30]. However, the manufacture of a large wind turbine will be hampered by factors like special reinforced materials and bespoke lifting vehicles, etc. [5].

3.3. Onshore wind farms across the world

A wind farm is a collection of wind turbines used to generate electricity by capturing wind power. A large wind farm can contain several hundred wind turbines and cover hundreds of square miles.

The United States owns the greatest number of wind turbines, and had the largest wind farm in the world as of 2010; it has great wind power potential [31]. Table 2 shows the top 10 wind farms in the world until 2010. It is obvious that most of the large operational onshore wind farms are located in the US, the biggest of which is the Roscoe Wind Farm; its installed capacity is 781.5 MW with 627 wind turbines. This project was finished in 2009, and covers an area of nearly 400 km^2 in Roscoe, Texas [32].

The Dabancheng wind farm in China is the only one in Asia in the top 10 wind farms list; it is also the largest operational wind farm in China. The installed capacity of Dabancheng wind farm is 500 MW, and it is located in Xinjiang Province [33]. However, the Gansu wind farm under construction now in Gansu Province, China, the installed capacity of which is planned to grow to 20 GW by 2020, will be the largest onshore wind farm in both China, and in the whole world in the future [34].

Europe also has large numbers of wind farms, while the amount of wind farms in Germany stays in second place after the United States. However, no single wind farm has an installed capacity large enough to step into the top 10 [30]. Nevertheless, with the rapid construction of large onshore wind farms all over the world, the list of the first 10 largest onshore wind farms will soon be changed. Table 3 shows the 10 largest proposed onshore wind farms in the world.

What is more, the largest onshore wind farm in Australia is the Hallett Group, with an installed capacity of 298 MW, and the

Table 3
Top 10 largest proposed onshore wind farms in the world [80].

Rank	Wind farm name	Capacity (MW)	Country
1	Gansu Wind Farm	20,000	China
2	Titan Wind Project	5050	USA
3	Pampa Wind Project	4000	USA
4	Markbygden Wind Farm	4000	Sweden
5	Dobrogea Wind Farm	1500	Romania
6	Silverton Wind Farm	1000	Australia
7	Hartland Wind Farm	500–1000	USA
8	Castle Hill Wind Farm	860	New Zealand
9	Shepherds Flat Wind Farm	845	USA
10	Sinus Holding Wind Farm	700	Romania

Table 4
Large offshore wind farms in the world [38].

Wind farm name	Capacity (MW)	Country
Thanet	300	UK
Horns Rev II	209	Denmark
Rϕdsand II	207	Denmark
Lynn and Inner Dowsing	194	UK
Robin Rigg (Solway Firth)	180	UK
Gunfleet Sands	172	UK
Nysted (Rϕdsand I)	166	Denmark

Table 5
Installed capacity (MW) of offshore wind farms in European countries [37].

Country	Installed capacity (MW)
UK	1341
Denmark	854
Netherlands	241
Belgium	188
Sweden	153
Germany	116
Ireland	22

Melancthon EcoPower Center is Canada's largest onshore wind farm, with an installed capacity of 199 MW [31].

4. Offshore wind

While onshore wind is developing by leaps and bounds, in the meantime, offshore wind has also attracted people's attention in recent years. As generally known, wind energy is clean and inexpensive, but space for the turbines is becoming scarce, which makes offshore wind an attractive choice. Therefore, offshore wind power has recently been widely focused on and developed, as it is reliable, intensive, and its source is abundant and offers vast offshore areas. It can not only ease reliance on oil and cut down emissions, but also stimulate the marine economy development and offer job opportunities.

4.1. Advantage of offshore wind

There is a growing interest in constructing wind towers offshore because offshore wind has many advantages compared with its onshore counterpart. The wind blows harder and stronger so that it can provide greater productivity when larger turbines are installed. With huge potentially productive areas available offshore, large wind farms can be built. Hence, the wind turbines are far enough away from the shore and human life that the issue of visual impact and noise can be ignored. Thus, it is possible to apply some efficient but noisy wind turbines, like two-blades and downwind ones. What is more, softer and cheaper blades can be used in a downwind turbine, as they would be deflected from the tower and could reduce the possibility that they would hit the tower [35]. Meanwhile, to make a smaller visual impact, bigger wind turbines can be built, so fewer are needed. However, bigger turbines may not necessarily be better because of the stresses caused by the blades' own weight [36].

4.2. Offshore wind scenario

4.2.1. Europe

Europe has always been the leader in offshore wind technology, and has developed much faster than other regions. The largest offshore wind farms are all distributed in Europe, as shown in Table 4. Until 2010, there are in total 39 offshore wind farms built across Europe of which the operating capacity hitted 2.9 GW [30]. The year 2010 was absolutely a record year for offshore wind development in Europe by adding 883 MW and, in the future, more than 100 GW of offshore projects will be constructed or under development in Europe [37]. The new offshore capacity was contributed by the United Kingdom (458 MW), Denmark (207 MW), Belgium (165 MW), Germany (50 MW) and Finland (2.3 MW), respectively [26].

In 2010, the total number of new, fully grid connected wind turbines was 308, a 51% increase from 2009 [38]. In the same year, eighteen European offshore wind farms were under construction, and eight of them were fully completed and grid connected [26]. The total offshore wind capacity in Europe in 2010 is shown in Table 5.

It is obvious that the UK is the leader in European offshore wind, with the largest installed capacity. Within the first half of 2010, 16 offshore wind farms were built in Europe with a total installed capacity of 743 MW, and 8 were in the UK with an installed capacity of 455 MW [37]. As of January 2011, the Thanet Offshore Wind Project in UK with 300 MW installed capacity is the largest offshore wind farm in the world, followed by Horns Rev II (209 MW) in Denmark, while the Greater Gabbard Project (504 MW) is the largest offshore wind farm under construction [39]. It is predicted that the total installed capacity of offshore wind in Europe will reach 40 GW in 2020, with the UK contributing half [37].

Looking back on the history of offshore wind, it is necessary to mention Denmark. Denmark is not only the second highest contributor to offshore wind in Europe, it is also a pioneer in this field; Denmark built the first wind farm in the world in 1991, and have been using wind turbines to supply electricity for nearly 20 years [6].

The first offshore wind turbine was installed in 1992; since then, offshore wind turbines have been increasing in both size and capacity at a faster rate than the onshore turbines. Until 2010, the 5 MW Multibrid and 5 MW Repower, both set in Germany, were the largest offshore wind turbines in operation [30].

4.2.2. China

The operation of China's first offshore wind farm, the Shanghai Donghai Bridge project, marks China's entrance into the offshore wind market. The Donghai Bridge offshore wind farm began generating power in June 2010. It is also the first offshore wind farm outside Europe. Furthermore, four projects along the coastline of Jiangsu Province add 1 GW of planned capacity of offshore wind [17].

4.2.3. The United States

The potential for offshore wind power in the United States is so enormous that it tops 907 GW, close to the generating capacity currently installed in this country [40]. As of 2009, America is still in the planning stages of exploiting offshore wind. Five offshore wind projects are currently planned: the Cape Wind project, the Bluewater Wind project, the LIPA offshore wind park, the Nai Kum project and a project developed by Wind Energy Systems Technologies LLC [35].

However, the Cape Wind project, approved by the Federal Government in April, 2010, is proposing America's first offshore wind farm on the Horseshoe Shoal in Nantucket Sound. Miles from the nearest shore, 130 wind turbines will gracefully harness wind to produce up to 420 MW. The project is designed to provide three quarters of the Cape and Islands' electricity needs [41].

4.3. Challenges and solutions of offshore wind technology

Although offshore wind technology has many advantages, there are still many challenges to its successful implementation. The cost of constructing a wind farm offshore is 1.5–2 times greater than

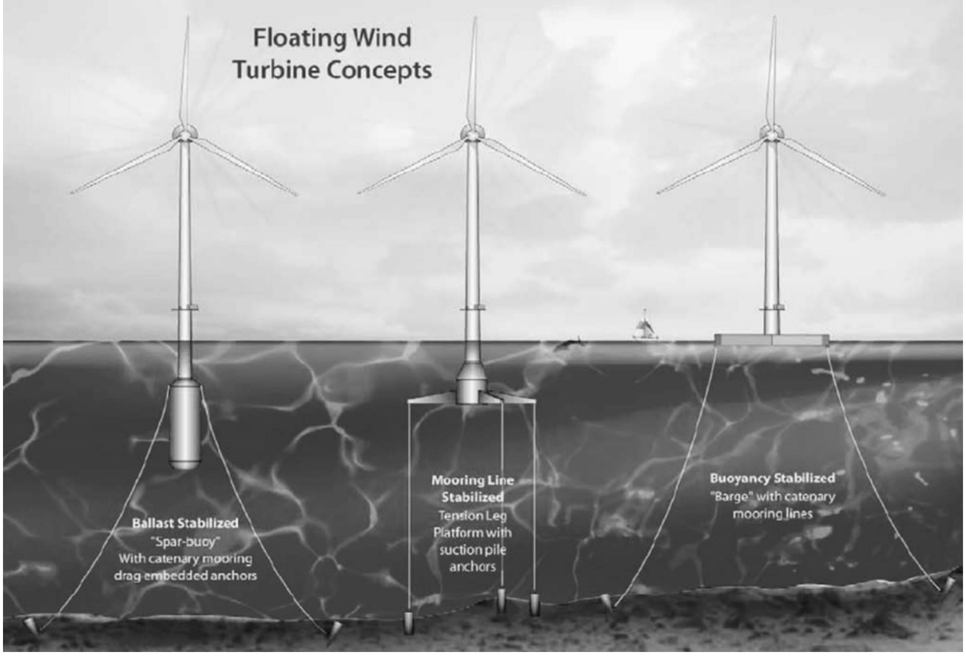

Fig. 3. Floating wind turbine concepts (from Ref [35], reprinted by permission of Elsevier).

that onshore, as the towers, foundations, underwater cabling and installation offshore are more difficult and expensive [42]. Since the offshore wind farm is far away from shore, maintenance and repair is also more challenging, due to the difficulty in accessing the site. What is more, the need for crane vessels in repair makes it 5–10 times more expensive than onshore repair [43].

Offshore wind is a comparatively new sector, but there is still a great deal to explore in its technology. Until now, almost all offshore wind farms are directly using onshore wind technology. Since the environment and operating conditions are much harsher, the reliability of offshore wind turbine components needs to be studied and proven. Therefore we need time to develop the optimal offshore wind technology. For instance, the first generation offshore wind machine, like the Siemens 3.6 MW turbine, has been developed and its performance closely monitored [27].

The main challenge to offshore technology is how to settle the wind tower in waters that lies deeper and further from the land, as wind speeds tend to increase with the distance from the shore, and it is possible to harness more energy from the wind. However, as the wind tower is set further away, its cost also increases sharply [44]. Current offshore wind power plants are restricted to waters shallower than 30 m, and the water depth is, to a large extent, affected by the supported foundation of the wind tower. The monopole and gravity-based foundation are two types generally utilized in shallow waters [35,45]. The monopole-based foundation with a diameter of 6 m is used in waters up to 30 m, while the gravity base foundation is mainly used at exposed sites in waters 20–80 m [38]. For waters more than 30 m in depth, a multiple footing design would be applied to the foundation to increase its stability [35]. For example, the tripod piled and tripod suction caisson foundations are also used in waters that are 20–80 m deep [38].

Meanwhile, when seeking to shift the wind turbine from the seacoast to deep water, floating wind turbines are one possible method; there are three main design concepts for this type of turbine. They are the Ballast Stabilized, Mooring Line Stabilized and Buoyancy Stabilized foundations, as shown in Fig. 3 [46,47]. In the Ballast Stabilized concept, ballast is used to get the center of gravity well below the center of buoyancy, providing stability; catenary mooring lines are used to keep the system in place. The Oceanwind Technology and Statoil Hydro companies are both studying this concept [4], which can be used in water depths from 200 m to 700 m.

The Mooring Line Stabilized concept uses Tension Leg Platform, the corners of which are connected to mooring lines anchored to the seabed. This concept is currently being investigated by NREL and MIT [48].

The idea of the Buoyancy Stabilized concept is to have the wind turbine stand on a platform floating near to the surface, and held in place by mooring lines. The mooring lines in this concept primarily have the role of keeping the structure in place. NREL and MIT are also working on this a concept to support a 5 MW wind turbine [48,49].

Moreover, a life cycle assessment (LCA) has been carried out to determine the environmental impact of a floating wind turbine on the marine areas. Compared with the results of conventional non-floating wind power plants, it shows that there is almost no difference between the two; a floating wind turbine can obtain larger wind resources, since it can be located further from the shore on a floating foundation [50]. The successful application of floating wind turbines in the near future will help offshore wind to develop much faster and generate more wind power.

5. Environmental impact

In contrast to fossil fuels and nuclear power, wind turbines do not pollute our atmosphere with greenhouse gases, nor do they cause any problems for future generations with radioactive waste. Thus, wind power is considered environmentally benign. However, it still imposes some impacts on human life. In particular, the potential long-term effects, although minor, cannot be ignored. Nevertheless, the impacts of wind turbines on our environment have not been well-established, and remain under debate.

In order to build a truly sustainable society, the environmental impacts of wind turbines should be further studied and solved. Some discussions and research on this topic have been carried out in previous years, and will be reviewed here.

5.1. Noise and visual impact

The inherent impact of wind turbines on its environment is always limited to the immediate surroundings. The noise caused by operating onshore wind turbines, and their visual impact, can be a major annoyance in people's lives [51].

Wind turbines cause noise in two main ways: mechanical noise and aerodynamic noise. The latter, although still lacking factual evidence of its impact, is considered to be a critical issue. Its low frequency may cause annoyance in people's lives; this problem has been argued by some experts [52]. However, some researchers believe this can be a serious problem for people living close to wind farms, and have done research and surveys on the topic.

Pedersen [53] has explored the relationship between the sound pressure levels of wind turbines and neighbors' well-being, showing that stress symptoms such as headaches appeared in those who were annoyed by the presence of wind turbines. Punch et al. [54], when reviewing and summarizing recent literature in this area, found that the low-frequency aerodynamic noise of wind turbines can bother people by causing sleep disturbances and hearing loss, and can also hurt the vestibular system. Some researchers have also mentioned possible solutions to this problem. For example, some suggested that wind turbines should be built at least 2 km away from where they live or optimize the house structure to block out the noise [52]. Son et al. [55] studied the characteristics of aerodynamic noise from wind turbines, using an integrated numerical methods based on Ray theory, and found that the noise of wind turbines can be significantly minimized by putting obstacles in the propagation path. The experiment carried out by Oerlemans et al. [56] shows that an optimized blade or serrated blade can reduce the noise level by, on average, 0.5 and 3.2 dB, respectively.

As for the visual impact, people seem to evaluate it subjectively [57]. Some people think that wind turbines are impressive looking and pleasant, while others have opposing views. Relevant surveys have shown that more than 70% of people in the UK do not have a negative opinion of wind turbines [58]. On the other hand, some tourism officials thought that wind turbines could damage local tourism [57].

Among all the effects on the environment caused by wind turbines, the visual impact is the most difficult to assess [8]. Many assessment methods, such as the Quechee Test, Multicriteria Analysis and the Spanish method, have been developed [59]. The Quechee Test is a theoretical evaluation aiming to assess whether the wind turbines would cause an adverse aesthetic impact to the landscapes, based on analytical factors closely related to the wind turbine and landscapes. Meanwhile, multicriteria analysis is currently a widely-used method, yielding an evaluation score from 0 to 100 by analyzing physical attributes (PA) (like water, land form, snow, etc.) and aesthetic attributes (like color, texture, etc.). On the other hand, the Spanish method uses a CAD software and a Geographical Information System to create a topographical solid surface, on which the wind turbines would be put to undertake the simulation; the value of PA, used to evaluate the visual impact level, is then calculated. The higher the PA value, the deeper the impact level [59,60]. By using the Spanish method, it is found that the quantification of potential visual impact can improve the public's acceptance of the innovation [61].

5.2. Effect on animals and birds

The danger of wind turbines to birds is a concern to many animal lovers, as wind farms may be built in the birds' habitats. Studies show that local birds can quickly learn to avoid obstacles, and thus that wind turbines would not be a serious problem for them [8]. Birds will still be killed by wind turbines, but the amount of birds that will be killed this way is negligible compared to the deadly results of other human activities such as deforestation and urbanization, no matter how extensively wind energy is used in the future [57]. Some measures can also be put in place to protect birds from wind turbines. In a wind project in Texas, avian radars are set to detect birds in the area; the system will stop the wind turbines if there is a potential danger to birds from the turbines [62]. Professional wildlife surveys can also be carried out before wind farm construction in order to understand the breeding and feeding behaviors of local birds, which helps to minimize the danger imposed on the birds [63].

Although offshore wind is a new industry sector, its impact on sea creatures in coastal areas has been studied by several researchers. A research has pointed out that some sensitive marine mammals, like dab and salmon, can perceive pile-driving pulses at a considerable distance during the construction and operation of wind turbines, thus, their behaviors can be affected by these offshore wind turbines [64]. Nevertheless, information in this area is still rare, and more studies need to be to be done as a result of increasing offshore wind construction.

5.3. Climate change

As the scale of wind farms becomes larger and larger, there are some speculations that they may cause changes in local climates. Two such cases have attracted general concern.

In Xilingo League, Inner Mongolia, precipitation data provided by the Water Statistics Bureau showed that there has been an unprecedented drought since 2005, and that this drought developed much faster in wind turbine areas [65]. Moreover, at the San Gorgonio wind fields in the US, when analyzing the temperature records of the wind farm Roy and Justin [66] found that giant wind turbines could change local temperatures by warming surface temperatures at night and cooling them in the daytime. This analysis indicates that giant wind turbines do have environmental impact, but whether the impact is good or bad still needs to be studied further.

Keith et al. [67] has simulated wind turbine's climatic impact by changing the drag coefficients of the surface in two different general circulation models, which shows that wind power can induce climate change at continental scales, but that its effect on the global average surface temperature is minor.

Furthermore, some environmental engineers speculate that the turbulence in the wake of wind turbines may cause local climate change by mixing the air up and down; this turbulence can be detected at long distances. The turbulence in the wake of the turbines can also change the direction of the high-speed wind at the surface, which would enhance local moisture evaporation [68].

In general, even though we cannot directly relate this irregular phenomenon to wind turbines at this moment, it is necessary to continue studying these effects, as more and more wind farms will be constructed in the next few decades. In summary, the environmental impact of wind turbines is a controversial topic. We cannot deny that all human behaviors will cause corresponding effects to the environment. However, as wind energy will become a main energy source in the near future, many environmental effects that now seem minor may cause disastrous impacts in the future, and therefore should not be ignored. Therefore, further research and proper optimization should be carried out, making wind power a friendly and sustainable way to generate electricity.

6. Wake effect and assessment using CFD method

6.1. Wake effect

Wake effect loss must be taken into account when calculating the efficiency of a large-scale wind farm, and as mentioned before, the climatic impact of wind turbines may be related to its wake effect. Thus, in order to determine how wind turbines may impact the local climate, it is essential to study the wake effect of wind turbines.

As early as 1988, Zervos et al. [69] has developed a numerical method without a grid, using the vortex particle concept to explore the wake structure of wind turbines. The simulation results were a good match with the experimental results, which showed the reliability of the developed method. In the same year, a comparatively simple numerical model was presented by Ainslie [70], which takes all the relevant meteorological factors into account to calculate the wake flow field of the wind turbine.

Different wake models have been developed, and Crespo et al. [71] reviewed them in 1999. Six commonly used models were evaluated based on an experiment that measured the offshore wake wind speed distribution by means of a ship-set sodar, which in turn established a new evaluation method [72]. Lee et al. [73] carried out a 3D simulation of wind turbines in mountainous areas to study the varied flow performance in complex terrains. The results can help researchers choose the building sites of wind turbines in this area. The frozen rotor method is also mentioned in this study, as a model for a rotating blade. Rathmann et al. [74] described a wind farm wake model that does not require any regularity of the wind farm layout in order to indicate the wake loss when evaluating wind turbine array efficiency. Wu et al. [75] used large-eddy simulation (LES) and a Lagrangian scale-dependent dynamic subgrid-scale (SGS) model to investigate the flow characteristics of the wind turbine wake. Results show that the tuning-free SGS model works well when compared with experimental results, and the actuator-disk model with rotation (ADM-R) presents better usability to detect the turbine-induced force. In 2011, Wu et al. [76] studied the atmospheric boundary layer flow and its interaction with wind turbines, using the same method to obtain the spatial profiles of turbulent wake characteristics.

Regarding the offshore wake part, the ENDOW project, which started in the year 2000 and lasted for 3 years, first comprehensively evaluated existing offshore wake models and then enhanced the wake and boundary-layer models to improve design tools for the planning of large offshore wind farms [77].

6.2. CFD method

As wind turbines are large and always cover a wide area, it is not easy to conduct experiments on a real wind turbine or in a wind farm. Therefore, computer modeling could play an important part in exploring wind energy. Therefore, when it comes to the research area of wake effect, noise, efficiency, wind blade, wind farm design, etc., simulation methods have always been used. During the past two decades, the CFD method has been popularly used in wind turbine numerical simulation [75]. Melheim [78] combined CFD with RANS based on a turbulence model and an “Actuator Disc” model, which proved to be a promising modeling method for studying wind farm wake loss. CFD software programs, such as STAR-CD and STAR-CCM+, have been developed to simulate the airflow of different turbine configurations that are stored in the software database. A recent project in Austria, Wind Giant, has utilized this software to demonstrate the feasibility of its new wind turbine concept [79].

In general, by using the CFD method, we can not only obtain extreme loading at pinpoints, but we are also able to get more data than from experimental methods.

7. Conclusions

At present, wind energy is a mature renewable energy source that has high potential to become a major primary source of energy in the future. Over the last decade, wind energy has developed by leaps and bounds. During this period, the world wind power generating capacity has grown rapidly, with an average annual growth of 29%. In mid-2010, the totally installed capacity increased to over 175 GW, and is estimated to hit 260 GW by 2012 and 425 GW by 2015. However, whether or not the development of wind power can maintain this pace and reach the target in the future is, to a large extent, decided by energy policies.

While most wind power development is onshore, offshore wind power is a comparatively new sector of wind energy that has attracted people’s attention due to its many advantages over onshore wind. European countries have thus far been leading the offshore wind market and technology. As of 2010, the cumulative capacity of offshore wind in Europe reached 3 GW. Countries like China and the United States are also making efforts to develop their offshore wind farms. However, offshore wind is a new technology that still needs to be tested in the tough marine environment, and its specific machines need further development.

Although wind power is believed to be environmentally benign, compared to conventional fossil fuels, it still has effects on animals and on human life, such as noise and visual impacts. In recent years, its climatic impact has drawn particular attention. These impacts may seem minor at present, but its potential long-term effects are not yet known, and thus cannot be ignored. With the development of wind power, the CFD method has been more and more frequently used in a variety of wind project studies, and has been used to predict its environmental impact.

In short, with proper and supportive policies towards wind power and a good understanding of its environmental impact, wind energy can be a clean and sustainable source of energy that can successfully replace fossil fuels.

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