CHAPTER 1

Introduction to Wind Power

R.S. Amano
University of Wisconsin-Milwaukee, Madison, WI, USA.

Abstract

Wind power is a well-proven and cost-effective technology and expected to be the main way in which industry responds to the Government's targets – so becoming an important source of electricity in years to come. In this book, we have focused on basic and some advanced topics needed to understand the current situation in the win power engineering. This chapter provides introductory materials for the wind energy.

Keywords: Introduction to renewable energy, wind energy in the world, fundamentals in wind turbines.

1 Introduction

As the clean energy industry emerges from initial stage caused by the global economic downturn, it is entering a new stage of rapid change of business. The worldwide demand for energy is expected to double by the year 2030 and triple by 2050, when fossil fuels will account for no more than two-thirds of all energy consumed, compared with 79% of the energy consumed today. Traditional fossil sources such as oil, gas and coal are not renewable and cause pollution by releasing huge quantities of carbon dioxide and other pollutants into the atmosphere, thereby damaging the environment in many ways, from acid rain to climate change. To help combat these problems, many states in the United States are seeking ways to use renewable energy sources, such as wind, solar and biomass. Along with its environmental and cost benefits, renewable energy is a rapidly growing industry with vast potential for economic growth and job creation. In fact, the U.S. Secretary of Agriculture has identified wind, solar and biomass as key factors for advancing the U.S. economy.

Wind energy has recently become the world's fastest growing source of renewable energy. The U.S. Department of Energy (DOE) expects that wind energy will contribute to 20% of the U.S. electricity supply by 2030. As a result, there has been

WIT Transactions on State of the Art in Science and Engineering, Vol 81, © 2014 WIT Press
www.witpress.com, ISSN 1755-8336 (on-line)
doi:10.2495/978-1-78466-004-8/001

a revived interest in wind turbines because they are emissions-free and wind is renewable and cost-free; however, the amount of electricity generated and obtained by wind energy conversion systems is still unsteady, relatively expensive and difficult to integrate into traditional electricity systems because of the variation in wind source and unresolved energy storage issues. On a large scale, spatial variability describes the fact that there are many different climatic regions in the world, some much windier than others. These regions are largely dictated by the latitude, which affects the amount of insolation. Within any one climatic region, there is a great deal of variation on a smaller scale, largely dictated by physical geography – the proportion of land and sea, the size of land masses and the presence of mountains or plains, for example. The resource map of wind energy in the United States [1] indicates that the vast majority of available wind is very unsteady; strong wind zones are concentrated in certain regions and not uniformly distributed throughout the nation, making wind power collection more difficult. Conversely, the easy-to-collect wind energy is primarily confined to remote locations, making electricity distribution difficult.

In the USA, while wind makes up only 2% of total electricity supply, it is one of the largest sources of new power generation in the country, second only to natural gas generation in terms of new capacity built each year since 2005. During the last few years, wind power in the United States has been increasing rapidly as shown in Fig. 1 [2]. Over 1,000 wind turbines >2 megawatts (MW) are already in commercial operation in the United States, and the year-end order for 338 GE 2.5-MW wind turbines for the Shepherd's Flat wind project in Oregon is the harbinger of a shift in orders towards such larger turbines. This forecast assumes that inventory will have been exhausted and that there will be a growing market for wind turbine orders in 2011 and beyond, spurred by a national Renewable Electricity Standard (RES). The trend towards larger turbines is driven by economics: taller turbines with larger swept areas produce more power at a lower cost per kilowatt-hour. The rapid quest for more electrical power, moving from 2 MW turbines in 2009 to 6 MW turbines being installed in early 2012 has led to the tower head mass being increased from 140 to 360 tonnes, with enhanced variations in structural loading and fatigue. Stabilisation at the current power level will enhance opportunities for consistent design and manufacture of the structures within a farm.

Total wind capacity in the USA reached 60,000 MW by the end of 2012, with commercial-scale wind turbines operating in 38 states. Wind power accounted for 35% of the country's new power-production capacity from 2007 to 2011, second only to natural gas. According to the American Wind Energy Association (AWEA), Texas leads the country as the state with the most installed wind power with 10,400 MW. Iowa remains a leader in wind generation with 3,675 MW installed; while California and Minnesota continue to harvest significant amounts of wind with 4,322 MW and 2,733 MW, respectively [3].

Although this is a significant growth for wind energy, it still only accounts for a small percentage of the U.S. electricity supply. The U.S. Department of Energy recently released a report that laid out a plan to reach 20% wind energy power by

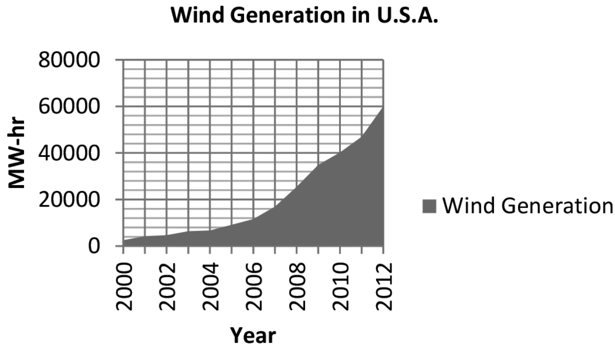

Figure 1: U.S. wind power generation (MW-hr).

2030 to fuel the U.S. electricity grid. This would provide a major increase in jobs, benefits to rural landowners and lead the Country to increased energy independence. Factors pushing for growth in U.S. wind energy include the high cost of fossil fuels and concern over national energy security. As a result, policy makers are actively considering a wide range of legislation that would support and enhance wind energy growth.

Progressive public policy has usually been a key ingredient both for encouraging wind energy expansion and helping to determine what forms that growth will take. Future growth will likely come from commercial-scale wind farms, which are typically vast arrays of turbines owned and operated by large corporations. Yet experience in Minnesota has shown that, with an encouraging policy environment, small clusters of turbines or even single turbines can make significant contributions, operated by local landowners, small businesses and community wind projects.

Worldwide there are now over two hundred thousand wind turbines operating, with a total nameplate capacity of 282,482 MW as of end 2012 [4] The European Union alone passed some 100,000 MW nameplate capacity in September 2012 [5], while the United States surpassed 50,000 MW in August 2012 and China passed 50,000 MW the same month [6]. World wind generation capacity more than quadrupled between 2000 and 2006, doubling about every 3 years. The United States pioneered wind farms and led the world in installed capacity in the 1980s and into the 1990s. In 1997, German installed capacity surpassed the United States and led until once again overtaken by the United States in 2008. China has been rapidly expanding its wind installations in the late 2000s and passed the United States in 2010 to become the world leader.

At the end of 2012, worldwide nameplate capacity of wind-powered generators was 282 gigawatts (GW), growing by 44 GW over the preceding year [7]. According to the World Wind Energy Association, an industry organisation, in 2010 wind power generated 430 TWh or about 2.5% of worldwide electricity usage [8] up from 1.5% in 2008 and 0.1% in 1997 [9]. Between 2005 and 2010, the average annual growth in new installations was 27.6% [10]. Wind power market penetration is expected to reach 3.35% by 2013 and 8% by 2018 [10]. Several countries

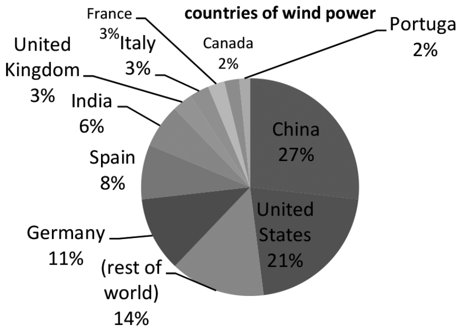

Figure 2: Top 10 countries by name plate wind power capacity (2012 year-end).

have already achieved relatively high levels of penetration, such as 28% of stationary (grid) electricity production in Denmark (2011) [11] 19% in Portugal (2011), 16% in Spain (2011), 14% in Ireland (2010) and 8% in Germany (2011). As of 2011, 83 countries around the world were using wind power on a commercial basis [12]. Figure 2 shows the top 10 countries by nameplate windpower capacity by the end of 2012.

2 Why do we need wind energy

The world is getting hotter, in fact by 1°C on land over the last 100 years, and the overwhelming consensus of scientific opinion is that human activities, particularly the emission of greenhouse gasses, are the cause [13]. The energy sector is by far the biggest source of these emissions, and if we are to tackle climate change it is clear that we need to move away from burning limited fossil fuel reserves to more sustainable and renewable sources of energy. As well as being good for the planet, this is also good for economy as it reduces the dependency on oil and gas imports – improving the balance of payments while also increasing energy supply security. We need to see more renewable energy and the Government has set a binding target for 20% of the USA's electricity to come from renewable sources by 2030 [14].

Wind power can play a major role in meeting USA's increasing demand for electricity, according to a ground-breaking technical report, 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply, prepared by the U.S. Department of Energy with contributions from the National Renewable Energy Laboratory, the AWEA, Black & Veatch and others from the energy sector. To implement the 20% Wind Scenario, new wind power installations would increase to more than 16,000 MW per year by 2018, and continue at that rate through 2030, as shown in Fig. 3. Wind plant costs and performance are projected to improve modestly over the next two decades, but no technological breakthroughs are needed. In the 20% wind scenario, 46 states would experience significant wind power development.

The report finds that during the decade preceding 2030, the U.S. wind industry could:

(a) support roughly 500,000 jobs in the United States, with an annual average of more than 150,000 workers directly employed by the wind industry;
(b) support more than 100,000 jobs in associated industries (e.g. accountants, lawyers, steel workers and electrical manufacturing);
(c) support more than 200,000 jobs through economic expansion based on local spending;
(d) increase annual property tax revenues to more than $1.5 billion by 2030 and
(e) increase annual payments to rural landowners to more than $600 million in 2030.

The report explores one scenario for reaching 20% wind electricity by 2030 and contrasts it to a scenario in which no new U.S. wind power capacity is installed. It examines costs, major impacts and challenges associated with the 20% Wind Scenario. It investigates requirements and outcomes in the areas of technology, manufacturing, transmission and integration, markets, environment and siting. The report finds that the Nation possesses affordable wind energy resources far in excess of those needed to enable a 20% scenario [15].

Wind power is a well-proven and cost-effective technology and expected to be the main way in which industry responds to the Government's targets – so becoming an important source of electricity in years to come.

Wind farms are created when multiple wind turbines are placed in the same location for the purpose of generating large amounts of electric power. Due to rising energy prices and the resultant search for alternatives, there are now thousands of wind farms in many countries around the world. There is still a lot of controversy surrounding the pros and cons of wind power and its local impact. The articles listed on this page explore news and information about wind farms. Now major electric companies are going green and proudly proclaiming it too from rooftops.

3 Current status on wind energy technology

Over the two decades, average wind turbine ratings have grown almost linearly seven times as large as 1980s (see Fig. 3). Each group of wind turbine designers has predicted that their machines are as large as they will ever be. However, with each new generation of wind turbines, the size has increased along the linear curve and has achieved reductions in life-cycle cost of energy. The long-term drive to develop larger turbines stems from a desire to take advantage of wind shear by placing rotors in the higher, more energetic winds at a greater elevation above ground (wind speed increases with height above the ground). For this reason, the capacity factor of wind turbines has increased. However, there are constraints to this continued growth to larger sizes as in general it costs more to build a larger turbine. The primary argument for a size limit for wind turbines is based on the 'square-cube law'. Roughly stated, it says that 'as a wind turbine rotor increases in size, its energy

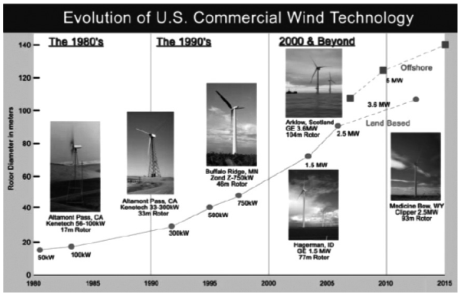

Figure 3: The turbine blade size growth over 25 years [16].

output increases as the rotor-swept area (the diameter squared), while the volume of the material, and therefore its mass and cost, increases as the cube of the diameter'. In other words, at some size the cost for a larger turbine will grow faster than the resulting energy output revenue, making scaling a losing economic game. Engineers have successfully skirted this law by changing the design rules with increasing size and removing material or by using material more efficiently to trim weight and cost. Studies have shown that in recent years, blade mass has been scaling at roughly an exponent of 2.3 instead of the expected 3, as shown by the WindPACT blade scaling study. The WindPACT study shows how successive generations of blade design have moved off the cubic weight growth curve to keep weight down as illustrated in Fig. 3. If advanced research and development were to provide even better design methods, as well as new materials and manufacturing methods that allowed the entire turbine to scale as the diameter squared, then it would be possible to continue to innovate around this limit to size [16].

4 VAWT and HAWT

Cross-wind-axis wind turbines most commonly oriented vertically and termed Vertical Axis Wind Turbines (VAWTs) have emerged as a potential unit to our need, after being shelved by wind turbine companies in the late 1980s as a result of the greater success of Horizontal Axis Wind Turbines (HAWTs). VAWTs present several advantages over HAWTs, however, which are especially pertinent in the built environment. There are, however, also significant challenges that have prevented their widespread adoption. These challenges must be overcome if VAWTs are to significantly contribute to meeting the 2030 wind power goal of the Department of Energy.

VAWT's have the equipment that needs maintenance nearer the ground. VAWT's are smaller (because if they were made bigger they would fly apart) and are used only in small applications – homes, office buildings, etc. where the reason is to make a statement. They make less than 50 kW. There are no commercial-sized VAWT's, because they do not make money, but if they existed they would spin at speeds from 1 mph to 100s of miles per hour. VAWTs would, of course, fly apart as soon as the wind went over about 20 mph, which is why they are not in commercial operation, as centripetal forces would break the blades. There are lots of types of VAWT's, because they are really all 'experimental' in nature, although some are in mass production. VAWTs cost less in total dollars, but significantly more in dollars per kilowatt generated (because they do not make much power for their cost).

4.1 VAWT drawbacks

Although several large test facilities have been built, these are for the most part no longer in operation. In addition to the principal advantages of wind turbines with a vertical axis – for instance, the low levels of noise and the independence from the wind direction – there are unfortunately several disadvantages. One of these is that they must be installed close to the ground. Since the wind naturally blows more strongly and evenly at greater heights, an installation that is not on a mast loses a great deal of efficiency. If with this type of installation, the generator is housed in a machine room on the ground, then the maintenance is of course simpler and cheaper. In spite of this, it is doubtful that the lower yield because of the weaker winds close to the ground would be balanced out by the money saved in maintenance costs. It still remains to be seen whether plans to use existing tall structures to mount planned megawatt-level installations with vertical spindles can be realized. It will probably not be easy to find buildings or structures that would be able to handle the static and dynamic loads from a large wind power installation with a vertical axis. And it goes without saying that these structures should be in regions where the wind velocities are of interest. Another point against the current conceptions of larger VAWTs is the greater material expenditure per square meter of surface covered in comparison to installations with a horizontal spindle. This is a significant additional cost factor that can hardly be compensated for by the theoretically better possible exploitation of strong winds or gusts.

The main disadvantage of VAWTs is their low efficiency relative to HAWTs. This is a result of the variable torque produced by dynamic stall experience by each blade as it passes around the azimuth. The blades of a HAWT, on the other hand, produce constant torque around the azimuth. A further disadvantage is the inability to VAWTs to self-start. By improving the torque and therefore power produced by VAWTs, and enabling self-start, the two main roadblocks to their adoption would be removed. This would enable the widespread adoption of VAWTs for low-wattage power generation in the urban and residential wind power markets. This will increase renewable power generation in the locations where most power is consumed, reducing the losses and costs associated with transmission. Furthermore, it will reduce the reliability on fossil fuel based power generation and relieve consumers from the price variations that result from this reliance.

4.2 VAWT advantage

VAWTs have several advantages over HAWTs in the urban environment. Because they operate with a lower tip speed than HAWTs, they are less noisy. They also

Figure 4: H-Darrieus VAWT.

have a better aesthetic due to their three-dimensional shape, making them popular with architects. HAWTs are sensitive to yaw and skew, experiencing decreases in torque and power due to the aerodynamic asymmetry on the rotor disc under such flow conditions. Due to the complexity of airflow in the urban environment, the wind direction is generally not perpendicular to the vertical, making this issue an important problem in this environment. VAWTs, however, are less sensitive to both yaw and skew [17]. A further advantage of the VAWT is the simplicity of the mechanical design and maintainability of the turbine system. Being based on a vertical shaft, VAWTs can be designed with all heavy components located at ground level, with the exception of a single bearing. This advantage is of particular interest to the residential power generation market, in which ease of repair is critical. Of the various configurations of VAWT that exist, the simplest is the H-Darrieus VAWT, illustrated in Fig. 4. One of its advantages is its ease of manufacture, since the blades can be extruded. This makes the H-Darrieus VAWT, in particular, less expensive to build. Even the curved and helical blades of the more common 'egg-beater' and helical VAWT designs are economic to manufacture than the tapered blades of HAWTs. By reducing the manufacturing cost of wind turbines for the home market, the installation cost is reduced, as is the return time on investment. This time is one of the main barriers to most renewable energy system in the home power market. On the other hand, the situation with smaller installations with a nominal output up to approximately 10 kW can be considered to be substantially different. At this level of output, there are very many applications, which until now could only be insufficiently covered with horizontal systems. In particular, horizontal installations come up against their limits when located in high mountain areas, in regions with extremely strong or gusty winds, or in urban areas. But also in regions with relatively constant winds, that is, where the conditions are ideal for systems with a horizontal axis, a VAWT can have its advantages, at minimum if the neighbours complain about the annoyance of the noise. There have already been reports of enraged neighbours who have settled the acoustical problems with firearms.

5 Conclusions

The use of wind energy was an old practice since thousands of years ago. However, this technology has revived due to the shortage of fuels and the environmental problems generated by the traditional energy resources. The last decade has seen a sharp increase in wind turbine generated electricity globally and is now well accepted with a large industry manufacturing and installing thousands of MWs of new capacity each year. Although there are exciting new developments, particularly in very large wind turbines, and many challenges remain, there is a considerable body of established knowledge concerning the science and technology of wind turbines. This book is intended to present some of this knowledge and to present it in a form suitable for use by students and by those involved in the design, manufacture or operation of wind turbines.

References

[1] Utility-Scale Land-Based 80-Meter Wind Maps. *Wind Power America.* U.S. Department of Energy—Energy Efficiency & Renewable Energy, 2013.
[2] American Wind Energy Association (AWEA). AWEA 3rd quarter 2012 Public Market Report, 2012.
[3] Wind Power in the United States. http://en.wikipedia.org/wiki/Wind_power_in_the_United_States
[4] GWEC Global Wind Statistics 2012. *Global Wind Energy Commission*. Retrieved 18 February 2013. 2012.
[5] EU wind power capacity reaches 100GW. *UPI.* October 2012. Retrieved 31 October 2012.
[6] China's on-grid wind power capacity grows. *China Daily.* 16 August 2012.
[7] Wind Power by Country. http://en.wikipedia.org/wiki/Wind_power_by_country. 2013
[8] World Wind Energy Report 2010. *World Wind Energy Association Report.* 2011.
[9] Wind Power Increase in 2008 Exceeds 10-year Average Growth Rate. *Worldwatch.org.* August 2010.
[10] BTM Forecasts 340-GW of Wind Energy by 2013. *Renewableenergyworld.com.* August 2010.
[11] Månedlig elforsyningsstatistik. *Danish Energy Agency.* January 2012, Vols. summary tab B58-B72.
[12] Wind Power. *Gree and Independent Future.* http://windivaenergy.com/index.php/wind-energy, 2008.
[13] Coriolis Energy. http://coriolis-energy.com/wind_energy/wind_index.html. 2013.
[14] 20 percent wind energy by 2030. http://www.20percentwind.org/20p.aspx?page=Overview. 2013.
[15] Energy efficiency and renewable energy. http://www.nrel.gov/docs/fy08osti/41869.pdf. 2013.

[16] Thresher, R., Robinson, M. & Veers, P., *Wind Energy Technology: Current Status and R&D Future*. National Renewable Energy Laboratory. 2008, NREL/CP-500-43374.
[17] Ferreira, C., Simão, J., *et al.,* Simulating dynamic stall in a 2D V modeling strategy, verification and validation with particle image velocimetry data.