Journal of Trends in the Development of Machinery and Associated Technology
Vol. 17, No. 1, 2013, ISSN 2303-4009 (online), p.p. 1-8

PROGRESS OF WIND ENERGY TECHNOLOGY

Barış Özerdem
Department of Energy Systems Engineering, Bahçeşehir University
34353 Beşiktaş - İstanbul
Turkey

ABSTRACT
This paper provides an overview of the progress of wind energy technology, along with the current status of wind power worldwide. Over the period of 2000-2012 grid-connected installed wind power has increased by a factor of more than 16. Due to the fast growth in wind market, wind turbine technology has developed different design approaches during this period. In addition to this, issues such as power grid integration, environmental impact, and economics are studied and discussed briefly in this paper, as well.
Keywords: wind energy, aerodynamic efficiency, power coefficient

1. INTRODUCTION
Efforts to harness wind for energy go back to the ancient times. Wind energy driven boats were sailed on the Nile River as early as 5000 B.C [1]. The earliest designed windmills had been used predominantly for pumping water and grinding grains in China, Persia, Afghanistan and India starting as early as 200 B.C. After the Crusade which took place between 11th and 13th century, concept of windmill had been carried to Europe. In contrast with the vertical axis design of those Asian countries, European mills had horizontal axis. The typical European windmill had been used a rotor of 25 m in diameter. In spite of mechanical energy extraction from wind for the past 7000 years, electricity generation from wind had been developed in the late 19th century. In 1891, Poul LaCour was the first to build a wind turbine generating electricity in Denmark. But it should be noted that, the industrialization era had been caused a gradual decline in utilization of wind power. Then, some Danish engineers improved the wind energy technology. This paved the way for some Danish companies to be forerunners for modern wind turbine generators. These turbines were the first to use the advancing knowledge of aerodynamics. Danish design was based on an upwind rotor with stall regulation. Similar efforts had been started in USA at almost the same period of time [2,3]. First commercially available American design was based on a downwind rotor with a variable pitch regulation. However, this type of design was not very successful. As a result, there was still little interest in using wind energy other than for remote dwellings in the first half of the 20th century . Only small windmills especially for agricultural purposes were popular. These windmills were operated fully self-regulated which helped to left them unattended. After World War II, besides the Danish design concept, the German engineers developed a new approach. Their wind turbine comprised fiberglass blades mounted on a teetering hub were known for its high efficiency. In the early 1970s, with the first oil crises, the interest in the power of the wind was increased all over the world. Especially financial support for research and development of wind energy in many countries became available. They used this financial support to develop MW range wind turbine prototypes.
Further incentives have led to the first wind energy boom in history. By the end of the 1990s, wind energy has re-emerged as one of the most important renewable energy resources [4]. Wind energy technology itself also moved very fast towards new dimensions. Today, it is obvious that, the extraction of power from the wind with turbines and energy conversion systems is an advanced industry.

2. CURRENT STATUS OF WIND ENERGY

The development of wind technology has triggered the growth of energy market, as well. As a result, wind energy is the fastest growing energy technology since the 1990s, in terms of percentage of yearly growth of installed capacity. It is seen that the world cumulative wind power installed is 282,430 MW in the year 2012, an increase in total installed wind power by a factor of more than 16 over the period of 2000-2012. Among the countries, the highest wind power developing country is China with the total installed power of 75,564 MW at the end of the year 2012 with 13,200 MW installed power in the last year period. The other main highest wind power developed countries are USA, Germany, India, UK, Italy, Spain, Brazil, Canada, Romania, Poland, Sweden, Mexico, and Turkey with the new installed power of 13,124, 2,439, 2,336, 1,897, 1,237, 1,122, 1,077, 935, 923, 880, 846, 801, and 506 MW, respectively. igures 1-2, and Table 1 show this growth, very clearly [5].

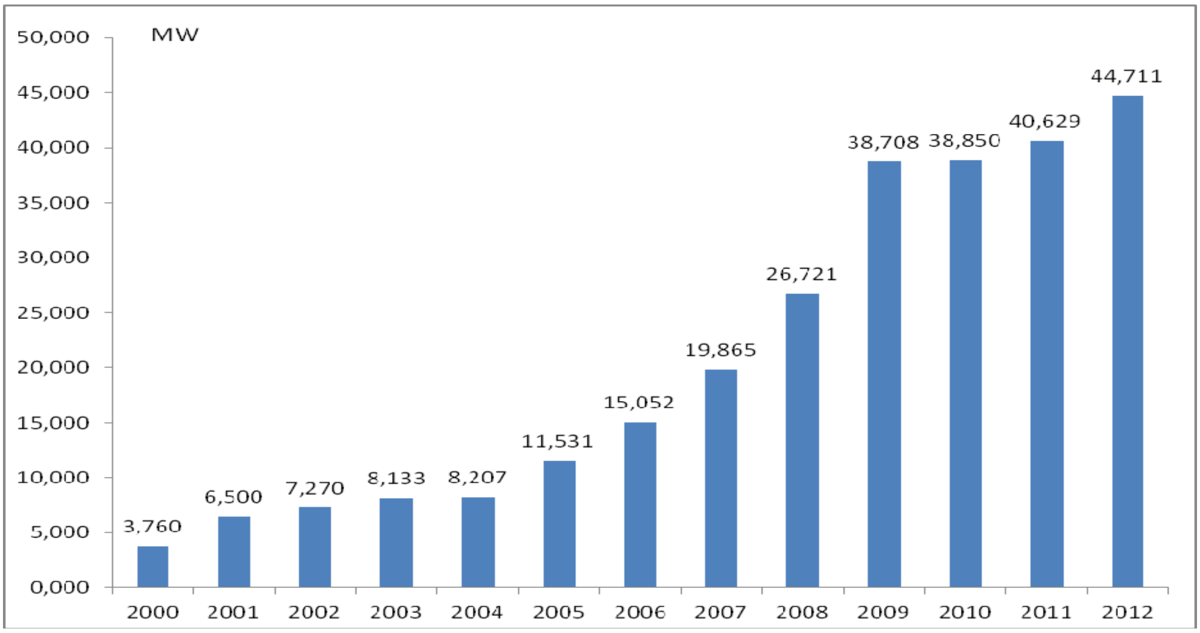

Figure 1. World annual installed wind power (2000-2012).

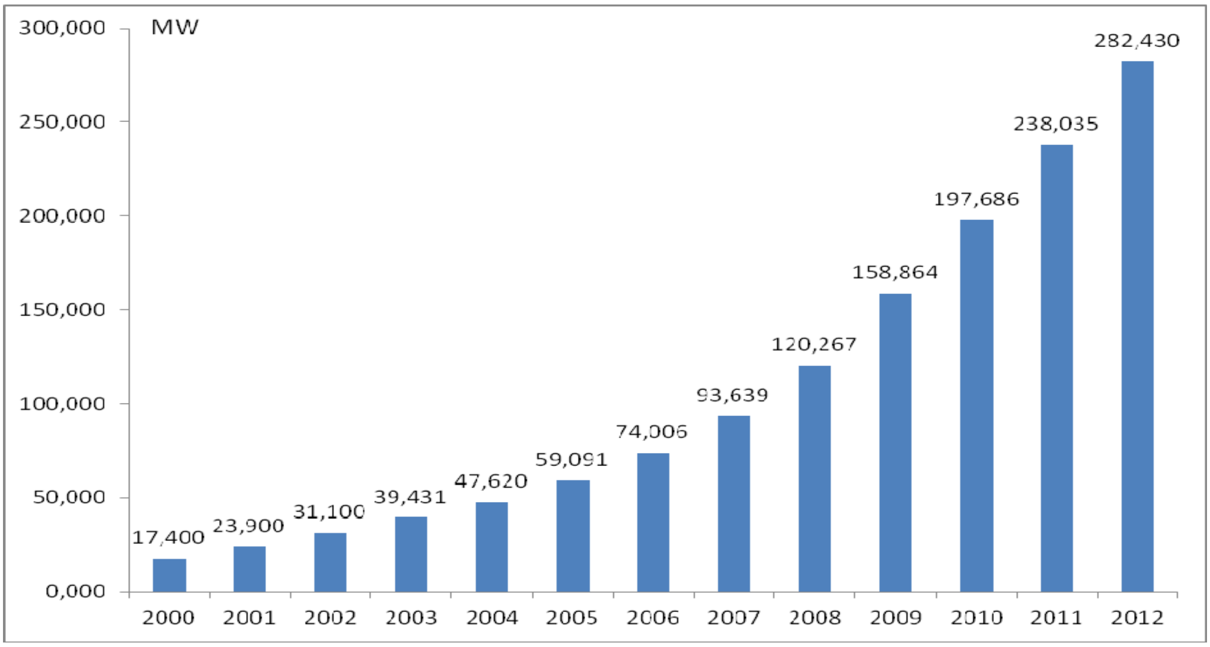

Figure 2. World cumulative installed wind power (2000-2012).

Table 1.Regional distribution of world installed wind power.

Region	Installed wind power (MW)	
	New installed in 2012	Total at the end of 2012
Europe	12,416	109,237
Asia	15,750	97, 810
North America	14,869	67,576
South America and Caribbean	1,225	3,505
Pacific	358	3,219
Africa and Middle East	102	1,135
Total	44,711	282,482

Based upon the Global Wind Energy Council Report published in 2013 regarding with wind statistics by the end of 2012, offshore installed wind power is reached to 5,410 MW in total with 1,292.6 MW new installed power in the year 2012. The highest offshore wind power developed in UK with 2,947.9 MW which corresponds to 54.5% of the total power. Then, the highest offshore wind power developments belong to Denmark, China, Netherlands, Germany, Belgium, Sweden, Finland, Ireland, Japan, Norway, and Portugal.

Small-scale wind energy refers to wind turbines rated less than 50 kW which are generally intended to supply electricity to buildings. These turbines may or may not be connected to the grid. Small wind turbines have been available in widespread use today, with reportedly over 150,000 machines installed worldwide [6]. More details regarding the overall installed power of small-scale wind turbines are not available. Small scale stand-alone wind turbines are usually used to power remote areas or remote technical applications. For electrification systems, wind turbines are utilized in combination with PV panels or a diesel generator backed up with a battery system. Stand-alone wind turbines are also used worldwide to provide mechanical power.

3. WIND TURBINE TYPES

Different type of wind turbines depend on their geometries and the airfoils or blades. Vertical axis wind turbines (VAWT) utilize the aerodynamic drag principle whereas, horizontal axis wind turbines (HAWT) utilize the aerodynamic lift principle. Savonius, Darrieus, Evans, and Musgrove rotors are examples for VAWTs. Although VAWTs catch wind from any direction without any adjustment, they cause fatigue failures and unwanted power periodicities at the output. As a result, most of the commercially available modern wind turbines are HAWTs which are based on the aerodynamic lift principle. Blades connected to the rotor may be upwind or downwind of the tower. Single, two, three, multi bladed rotors are examples for HAWTs. Especially three- bladed rotors are more common for electricity generation. They have higher rigidity and operate smoothly. Gearing mechanism and generator are in a case called nacelle at the top of the tower [7].

4. THE PHYSICS OF WIND

The air masses move due to the pressure difference resulting from the non-uniform heating of earth's surface by the sun. This motion of air masses is called wind. The wind which is driven by the temperature difference is called the geostrophic wind, or more commonly the global wind. Global winds, which are not affected by the earth surface, are found at higher heights. The rotation of earth contributes to another phenomenon near its surface called the Coriolis effect. Because of the Coriolis effect, the direct motion of air mass from the high pressure region to the low pressure region is deviated. The local phenomenon is determined by orographic conditions such as surface structure of the region. The energy is transferred from the geostrophic wind to the below layers as well as by local conditions. Since wind speed and direction change with height and local conditions, wind turbines experience different loads across the rotor.

The power of the wind is proportional to the air density, ρ (kg/m^3), area, A (m^2),and wind speed , V (m/s) to the third power.

$$P_{wind} = ½\ \rho\ A\ V^3\ (W) \qquad (1)$$

The power in wind is converted into mechanical energy by wind turbine. The wind power cannot be extracted completely by a wind turbine. The theoretical maximum power extracted by a wind turbine was first determined by Betz Š4review2000Ć. Hence, the theoretical maximum power extracted from the wind is;

$$P_{turbine,\ max} = ½\ \rho\ A\ V^3\ C_{p,max}\ (W) \qquad (2)$$

where $C_{p,max}$ known as Betz criterion is 0.5926. But Betz criterion does not consider any dynamic effects. Hence, power extraction efficiency will decrease from the maximum value. Glauert's criterion is an another dynamic calculation approach which helps to describe the variation of power coefficient, C_p, with tip speed ratio, λ . When rotational frequency of the wind turbine matches to particular wind speeds, then the optimal efficiency is obtained. If tip speed ratio, λ, is defined as ;

$$\lambda = V_{tip}/\ V_{wind} = \omega R\ /\ V_{wind} \qquad (3)$$

where R (m) is radius of rotation, ω (rad/s) is angular velocity. Betz criterion and the relationship of power coefficient, C_p, and tip speed ratio, λ, are shown in Figure 3 for a variety of turbines.

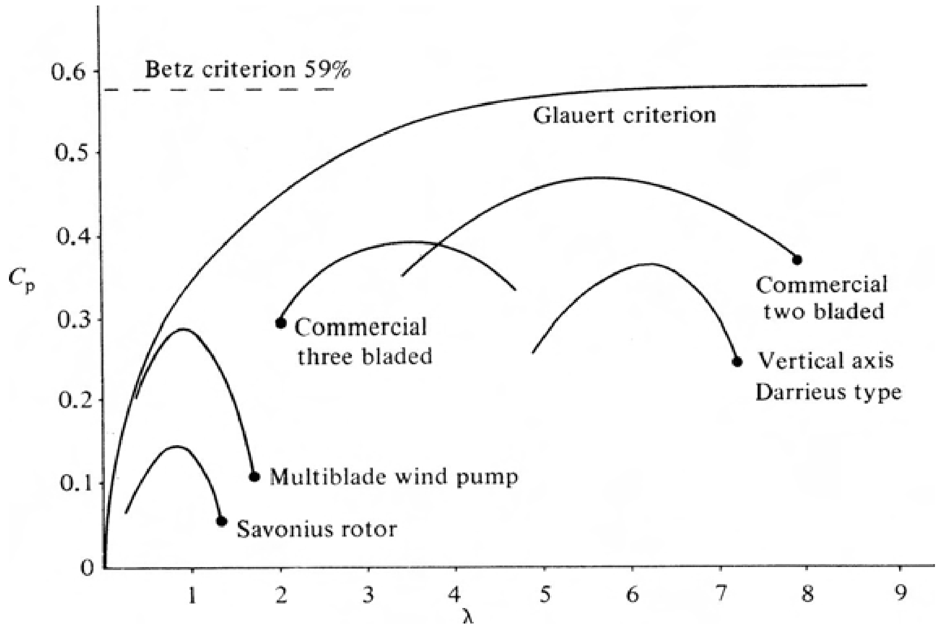

Figure 3. Power coefficient, Cp, as a function of tip-speed ratio, λ, for variety of wind turbines [7].

5. THE TECHNOLOGY OF WIND TURBINE

Since the commercialization of large-scale wind turbines in the 1980s, many technological developments are in progress. The design of wind turbines evolved from the use of simple, light materials driven by aerodynamic drag forces to advanced, heavy materials driven by aerodynamic lift forces. As a result, the size of the wind turbines have increased by a factor of 100 while the cost of electricity has reduced by a factor of more than 5 [8]. For modern HAWTs, the wind energy is extracted by means of a three-bladed horizontal upwind rotor. Blades can be pitch controlled for constant rotational speed of a shaft. Some design attempts are made for one and two bladed HAWTs in the last 30 years. Single blade design was structurally efficient. But due to the rotor balancing counterweight, aerodynamic efficiency is reduced. Increasing the number of blades from one to two yields a 6% increase in aerodynamic efficiency. Increasing the number of blades from two to three yields an additional 3% aerodynamic efficiency [9]. Three bladed HAWT does not cause too much disturbance for the next blade, as well [10]. So, it was proved that HAWTs are more efficient for large–scale wind energy harvesting. Since, the power output of a HAWT is not designed for very high wind speeds because such wind speeds occur rarely, all the HAWTs use some power control mechanisms. First, the pitch control mechanism which sends the signal to the blade that turns the rotor out of wind. Secondly, the stall control mechanism which prevents the blade lift force acting on the rotor to cause turbulence.

The main problem in establishing wind farms is the required substantial area to harvest the energy. Modern wind farms which consist of HAWTs require sufficient space for separation of them from each other. Typical land area for a HAWT is 0.25 acres. But this land area does not include the 3 to 5 turbine diameters in the cross-wind and 6 to 10 turbine diameters in the downwind directions. In order to increased the swept area of HAWTs, land area must be increased definitely. This causes the wind farms comprised of HAWTs to be established at remote sites. Consequently, this also increases the cost of energy due to added grid system. But the swept area of VAWTs can be increased without increasing the land area.

HAWTs can be designed differently. Basic design approaches for grid- connected ones are: three blades, moderate tip speed ratio, control optimization, mechanical and electrical innovations such as variable speed generators, etc. Each design approach shows high degree of freedom regarding the details. For instance, if the site has high wind speed values smaller rotor dimensions should be used. Aerodynamic airfoil also should be selected as maximum efficiency will be reached at high speeds such as 16 m/s. For low wind speed sites, larger rotor dimensions should be used. And aerodynamic airfoil should be selected as maximum efficiency will be reached at low speeds such as 12 m/s.

Three- bladed HWATs dominate the grid connected market. Although two-bladed ones are more lighter constructions, three-bladed ones have better moment of inertia, lower noise, and better visual aesthetics. As it is mentioned above, wind turbines reach the highest efficiency at wind speeds between 16 and 12 m/s. Power output should be kept at rated power for higher wind speeds by using stall, pitch , and active stall regulations. Stall regulation which needs constant rotational speed is achieved by using induction generator. But at certain wind speed known as cut-out, the turbine must be shut down. Pitch control system can have hydraulic or electric motors for pitching the blades. Once certain wind speed is reached, the rotor idles. Although the pitch controlled turbines are lighter due to lower thrust force, power oscillations are smaller for stall regulation type turbines. Active stall regulation is combination of pitch and stall and contents both systems' advantages. The wind turbines which have directly driven synchronous generators are rarely used for grid-connected wind turbines. They are applied in stand-alone systems mostly where the synchronous generators can be used in the isolated network.The decoupling of grid and the generator allows a variable speed operation of the generator system. It is important that the maximum power coefficient occurs only at a single tip-speed ratio. With a variable generator, the rotor speed can be accelerated and decelerated in accordance with the variations in the wind speed in order to maintain the single tip-speed ratio [4]. Due to the unpredictable nature of wind energy, energy storage and conversion are also the areas of interest. Some electrical energy storage technologies are: batteries, flow batteries, fuel cells, flywheels, superconducting magnetic energy storage, super capacitors, compressed air energy storage and pump hydo. The promising battery technologies are advanced lead-acid, sodium sulfur, and lithium ion [8].

6. ECONOMICS

Many studies showed that wind energy is an economically efficient resource. Approximately 75% of the total cost of energy for a wind turbine is related to the costs such as turbine, foundation, electrical equipment, grid-connection. Wind turbines do not use fuel and are operated automatically. Thus a wind turbine is capital-intensive compared to conventional fossil fuel Technologies. Their utilization saves fosil fuel, hence reduces adverse environmental effects. With the average wind speeds between 7 and 8 m/s, the cost of electricity is between 4 to 5 cents/kWh. This cost is a combination of the cost of build and operate, and the amount of energy produced over the wind farm's lifetime. The cost for manufacturing wind turbines declined by about 25% every time the number of manufactured wind turbines doubled. Innovations in design, materials, process and turbine up-scaling contributed this reduction alot. The Danish Energy Agency predicts that a further cost reduction of 50% can be achieved until 2020. This indicates that energy cost from wind power could be reduced more in the future [11]. But the potential for further cost reduction is not easy to estimate. A general comparison of the electricity production costs is very difficult as production costs vary between countries, due to the availability of resources, different tax structures or other reasons. In addition, market regulations can affect the electricity prices, as well.

Offshore wind cost is still around 50% more expensive than onshore wind cost. However, due to the higher wind speeds and the lower visual impact of the larger turbines, predominantly European countries prefer to establish offshore wind farms. Although the investment costs are considerably higher for offshore than onshore wind farms, total electricity production from the offshore turbines is higher. Higher offshore wind speeds at longer hours in a year cause this advantage. An average operation time is more than 4,000 full load hours for a typical offshore wind farm [12].

7. ENVIRONMENTAL IMPACT

Wind energy can be regarded as environmentally friendly resource. Its environmental impact slightly higher than the environmental impact of hydro energy on a life cycle basis. But it is stil not free of emissions. Because, the production of many components such as blades, nacelle, tower, etc., and the transport of them leads to the consumption of fossil fuel based energy resources. A study found the CO_2 emissions of wind power to range from 14 to 33 tonnes per GWh of energy produced. Most of the CO_2 emission comes from producing the concrete for wind-turbine foundations [13]. These emissions are known as indirect emissions. In addition, the noise and the visual impact of wind turbines are important considerations particularly, if the wind turbines are located close to urban areas. The noise impact can be reduced with appropriate siting of wind turbines in the site and by usage of variable speed generators, etc. There are reports of bird and bat mortality at wind turbines. Prevention and mitigation of wildlife fatalities may affect the siting and operation of wind turbines.

Wind farms may affect weather in their immediate vicinity. Spinning wind turbine rotors generate a lot of turbulence in their wakes. This turbulence increases vertical mixing of heat and water vapor that affects the meteorological conditions. A number of studies have used climate models to study the effect of extremely large wind farms. A simulation study that uses 10% of the world's land area reports changes in global climate. Wind power has a negligible effect on global mean surface temperature, and it would deliver "enormous global benefits by reducing emissions of CO_2 and air polllutants [14]. Another peer-reviewed study suggested that using wind turbines to meet 10 percent of global energy demand in 2100 could actually have a warming effect, causing temperatures to rise by 1 °C in the regions on land where the wind farms are installed, including a smaller increase in areas beyond those regions.

8. CONCLUSIONS

The main conclusions of this paper are :

- China has gained the first position with the installed capacity of 75,564 MW at the end of 2012.
- The total installed wind power is reached to 282,482 MW at the end of 2012 all over the world.
- Within the last 30 years, wind turbine sizes are enlarged more than 10 times.
- Three-bladed HWATs are the most economical and effective wind turbines.
- Since maximum power coefficient occurs only at a single tip-speed ratio, a variable generator can be very effective in order to maintain the single tip-speed ratio, hence maximum power coefficient.
- Due to the unpredictable nature of wind energy, energy storage technology must be developed.
- Wind energy can be regarded as environmentally friendly resource eventhough it is not emission-free.
- The adoption of any new technology takes time to be recognized.

9. REFERENCES

[1] Patel, MR: Wind and solar power systems, CRC Press, New York 1999.

[2] Hau, E: Wind turbines, Springer, Berlin 2006.

[3] Spera, DA: Wind turbine technology, ASME, New York 2009.

[4] Ackerman,T, Söder, L: Wind energy technology and current status: a review, Renewable and Sustainable Energy Reviews, 4, 315-374, 2000.

[5] Global Wind Energy Council, Global wind statistics 2012.

[6] American Wind Energy Association, Small scale wind energy report, 2008.

[7] Twidell, J, Weir, T: Renewable energy resources, E&FN SPON, New York 1996.

[8] Islam, MR, Mekhilef, S, Saidur, R: Progress and recent trends of wind energy technology, Renewable and Sustainable Energy Reviews, 21, 456-468, 2013.

[9] Milborrow, D: Wind energy technology, Journal of Power Energy, 216, 23-30, 2002

[10] Toft, H.S, Sorensen, J.D: reliability-based design of wind turbine blades, structural Safety, 33, 333-342, 2011.

[11] Surensen M, P: Learning curve: how are new energy technology costs reduced over time? Report of an IEA Workshop: Energy Technology Availability to Mitigate Future Greenhouse Gas Emissions, International Energy Agency, Paris 1997.

[12] European Wind Energy Association, The Economics of wind energy: A report by the EWEA, Brussels 2009.

[13] White,S, W: Net energy payback and CO_2 emissions from three Midwestern wind farms: An update, Natural Resources Research, 15, 271-281, 2006.

[14] Keith, D, W, et al.: The influence of large scale wind power on global climate, PNAS, 101, 16-115-16120, 2004.