Wind

57

Elvir Zlomusica

Abstract

Wind farms have seen their extreme growth and development since the signing of the Kyoto protocol. In 5 years (2007–2011) the capacities have more than tripled. In 2011, about 75 countries worldwide had commercial wind power installations, and 22 countries in the world already have more than 1,000 MW of installed capacities. Europe has also seen an increase of offshore markets. This is mainly related to the UK, Denmark, and Belgium. When the shares of production technologies for electricity production are analyzed, the proportion of the use of wind energy in the world is 2.2%. With the development of technology, technical characteristics of wind turbines and wind parks have significantly improved. Special attention is nowadays paid to those elements of wind turbines that showed certain shortcomings during the previous period, i.e., transmission mechanisms, generators, blades, etc. The availability of the present wind turbines is 98%, and the level of utilization is constantly increased, as well as the economic life with the modern machines that are nowadays projected for 25-year time period. There is currently an intensive work underway on new construction designs.

Wind turbine economics are changing rapidly, because of the new turbine producers, expansion of wind energy, initiatives for RES, etc. Nevertheless, it can be concluded that the price of electricity generated from wind farms becomes more and more comparable with the price of electrical energy produced from "conventional" fossil fuels. However, the only cases where they are completely comparable are the very large wind parks that are located at places with excellent wind characteristics.

Central critical points of some wind turbine project are turbine purchase contract, financing, liquidity, wind turbine repair, and annual variations of

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wind climate. Also, other factors affect the economics of wind farm, including depreciation, income taxes, and initiatives.

Wind turbines have some negative as well as positive impacts on the environment. Benefits of wind energy are different and very important. Experience in the implementation of wind projects in the EU shows that social acceptance is very important for the successful development of wind energy. Three key dimensions of social acceptance have been identified: community acceptance, market acceptance, and sociopolitical acceptance. The chapter presents the state of the art, design, wind turbine parts, efficiency, emissions, and economic analysis on these issues.

1 Introduction

The first attempts at generation of electrical energy from wind date back to the end of the nineteenth and the beginning of the twentieth century (James Blyth, Scotland, Charles F. Brush, Cleveland, USA, Poul la Cour, Denmark, etc.).

This was followed by a long time period with a huge number of different construction designs of wind turbines. Among others, it was noted that in 1940 in Vermont (USA), air-profile blades were introduced in the construction of wind turbines (Smith-Puntam).

Big energy crises in 1970s placed the wind turbines more in the spotlight. A period with different construction solutions (single-blade, double-blade, three-bladed, horizontal, vertical, and other wind turbines) ensued. An aspiration was toward big dimensions and powers. Some of those solutions were more; others were less successful. Some of them were very expensive. In any case, the construction technology did not sufficiently go hand in hand with the constructive elements design.

EU was the first one to recognize the possibilities and the importance of renewable energy sources, the energy of the wind among them. Thus, EU was the first to set its goals in mid-1990s. Until now, these goals have been fulfilled every time by the set deadlines. On the other hand, the goals set at the beginning of the new millennium (Directive 2001/77/EC) have been a subject of intensive discussions for a number of years already. In 2008, the biggest number of capacity was added in the wind energy for the first time in EU.

Wind farms have seen their extreme growth and development since the signing of the Kyoto protocol (1997), Fig. 57.1. In some countries and/or their parts, this growth is comparable even with the development of mobile telephony.

At that time, Denmark set up an example of its own. One can say that Denmark found itself "at the right time at the right place." So, even today Danish companies are bigger producers of wind turbines in the world. As an example, almost 26% of the electric energy supply in Denmark comes from the energy of the wind (Wind in Power 2011) (38% in January 2007 or according to the information from the system operator web site, in the morning of 13 September 2011, the wind turbines in Denmark generated 64% of total electricity production).

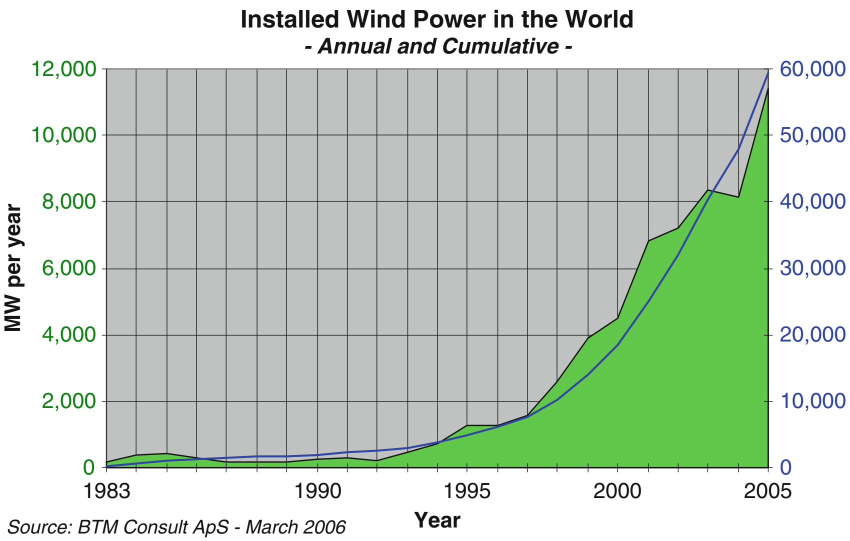


Fig. 57.1 Growth of installed capacities (BTM Consult 2006)

Among other countries, one should especially mention Germany, which, in 2008, had the biggest number of installed capacities in the world. Namely, in these countries, the space resources for installing the wind parks are almost completely exhausted. They are setting their future goals on the basis of repowering and opening of offshore markets.

2 Technology and Components

2.1 Wind Farm Market

At the end 2011, wind farms with a the total of 238,351 MW were installed throughout the world (Global Wind Statistics 2012). For the sake of comparison, in 2006 there were 74,052 MW installed, Fig. 57.2. So, in 5 years the capacities have more than tripled. Thus, all realistic expectations were surpassed. If it is looked at the values from 11 years ago (18,000 MW in the year 2000), the results are even more significant. Globally, the ten countries with the most installed wind capacity are shown in Table 57.1. For the first time, in 2011, Denmark is not among the top 10.

By the end of 2002, 75% installed capacities were in Europe, 15% in USA, and 10% in the rest of the world. In 2006 the data was as follows: 65% in Europe, 15.6% in USA, and 19.4% in the rest of the world (with a significant share of India with 6,270 MW or 8.4% and China with 2,604 MW or 3.5%). Therefore, that proportion has changed and keeps changing, so that in 2011 in Europe there was

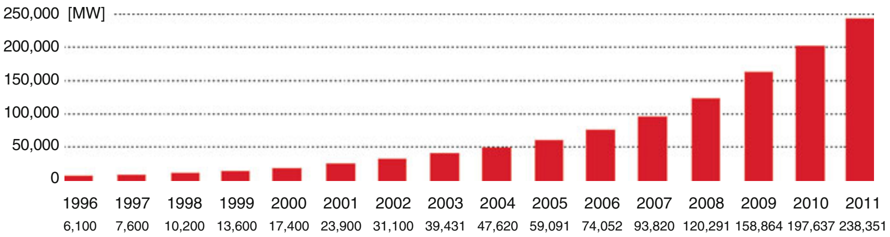


Fig. 57.2 Capacities installed in the world on 1996–2011 (Global Wind Statistics 2012)

Table 57.1 Top 10 countries by installed capacities at the end of 2011 (Global Wind Statistics 2012)

Country	MW	%
China	62, 733	26.3
USA	46, 919	19.7
Germany	29, 060	12.2
Spain	21, 674	9.1
India	16, 084	6.7
France	6, 800	2.9
Italy	6, 747	2.8
UK	6, 540	2.7
Canada	5, 265	2.2
Portugal	4, 083	1.7
Rest	32, 446	13.6
Total top 10	*205,905*	*86.4*
World total	*238,351*	*100*

40.5%; in Asia, 34.6% (26.3% in China, 6.7% in India); and in USA, 19.7% installed capacities of total installed capacities in the world. Of total capacities added in 2011, China installed 44%.

Today, about 75 countries worldwide have commercial wind power installations. There are 22 countries in the world already, of which in Europe as many as 15 countries, with more than 1,000 MW of installed capacities. Five years ago, this was 13 countries, of which 8 in Europe. As far as Europe is concerned, Germany and Spain have more than 50% of total installed capacities (Wind in Power 2011).

In the EU, 9,616 MW of wind energy capacity was installed in 2011, for a total installed capacity of 93,957 MW – enough to supply 6.3% of the EU's electricity, according to the European Wind Energy Association (EWEA).

Thanks to the 16,500 MW added in 2010, a few years before the estimates were made, China took over the first position by installed capacities from the USA, and the USA took over that place from Germany in 2008. In 2011 China added "incredible" approx. 18,000 MW. Also, China has considerable plans in the next period, 100 GW by the year 2020 (China Increases Its Wind Power 2009; China Boosts Wind Power Target to 100 GW by 2020). Also, in 2010 China became the world's largest producer of wind turbines.

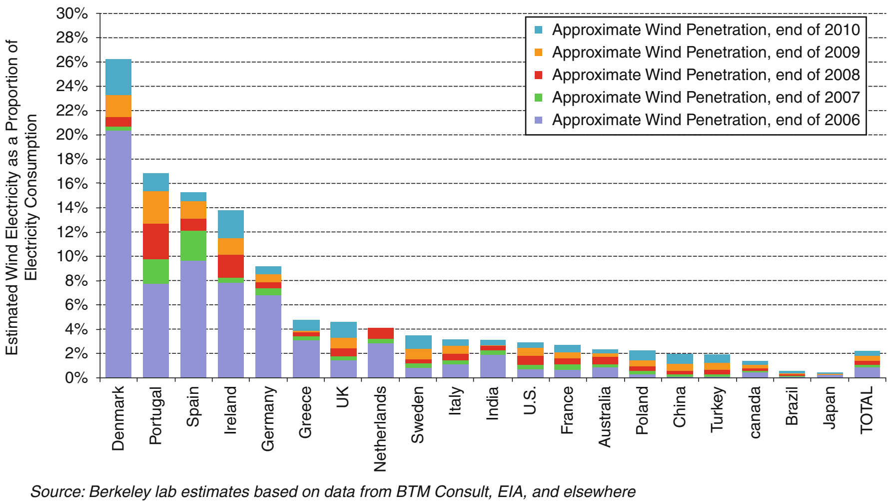


Fig. 57.3 Top 20 countries using the wind energy (2010 Wind Technologies Market Report)

Europe has also seen an increase of offshore markets. This is mainly related to the UK, Denmark, and Belgium (Wind in Power 2011). EU has set its goals for RES by 2020. Specific values have been set for each EU member country. As for the energy of the wind, the estimates and forecasts are both different and optimistic (180–230 GW). This implies creation of over 2,000,000 new jobs in this sector by 2020. These optimistic goals can be achieved by intensifying offshore markets and by opening offshore parks, the implementation of which is currently below expectations.

Figure 57.3 shows 20 countries that use the wind energy for electricity generation the most. As previously said, Denmark is in the first place and is followed by other European countries (Portugal, Spain, Ireland, Germany, etc.), while the first non-European country taking the tenth place is India. According to the diagram in Fig. 57.3, and according to the other available data, when the shares are analyzed of production technologies for electricity production, the proportion of the use of wind energy in the world is 2.2%.

3 Trends in the Development of the Industry of Wind Turbines

With the development of technology, technical characteristics of wind turbines and wind parks have significantly improved.

As an illustration of that, Fig. 57.4 shows a constant increase in size (rotor diameter and hub height) and the power of wind turbines during the period 1998–2010.

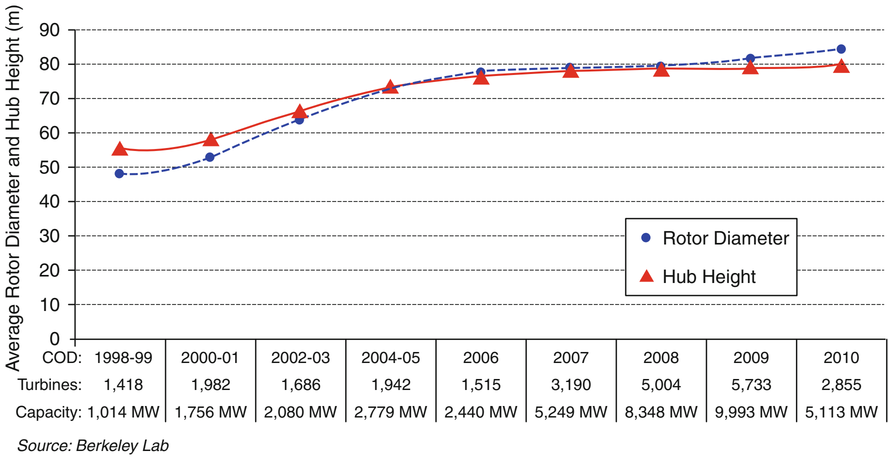


Fig. 57.4 Increase in rotor diameter and hub height (2010 Wind Technologies Market Report)

Since the cost of design, transport, mounting, and electrical infrastructure is minor for total investment, if the installed power is higher, it is economically more justified to use big wind turbines at the localities with good wind characteristics.

According to the statistical data, the average installed power of an individual wind turbine in the year 2011 in Germany was 2,243 MW (Ender 2012).

Special attention is nowadays paid to those elements of wind turbines that showed certain shortcomings during the previous period, i.e., transmission mechanisms, generators, blades, etc. The availability of the present wind turbines is 98%; the level of utilization is constantly increased, as well as the economic life with the modern machines that are nowadays projected for 25-year time period. Certainly, all this is thanks to the 20-year operational experience in this field.

There are a large number of wind turbine producers in the world today. There are certainly both a lot of similarities and differences between them. In the last 7–8 years, some new producers of equipment appeared, mostly huge multinational companies (General Electric (GE), Siemens, Mitsubishi, etc.), which, together with the already existing producers, have been leading to intensive improvement of wind turbine characteristics and reduction of its prices (Van Kuik et al. 2006). Figure 57.5 shows percent of various wind turbine producers in total production for 2010.

A few years ago, 70% of wind turbines in the world were produced by the European companies. As two typical representatives of this concept of the development of wind turbines, two companies specialized in that production have imposed themselves Vestas and Enercon. A decrease of share of these companies in the world's production of wind turbines may first of all be explained by the expansion of RES market, i.e., of wind farms in the other areas in the world. Namely, it is indicative that the companies in those countries where big capacities are being installed have increased their share (e.g., in the USA, General Electric Wind; in China, Sinovel, Goldwind, Dongfang, United Power (Ender 2006, 2008, 2009)).

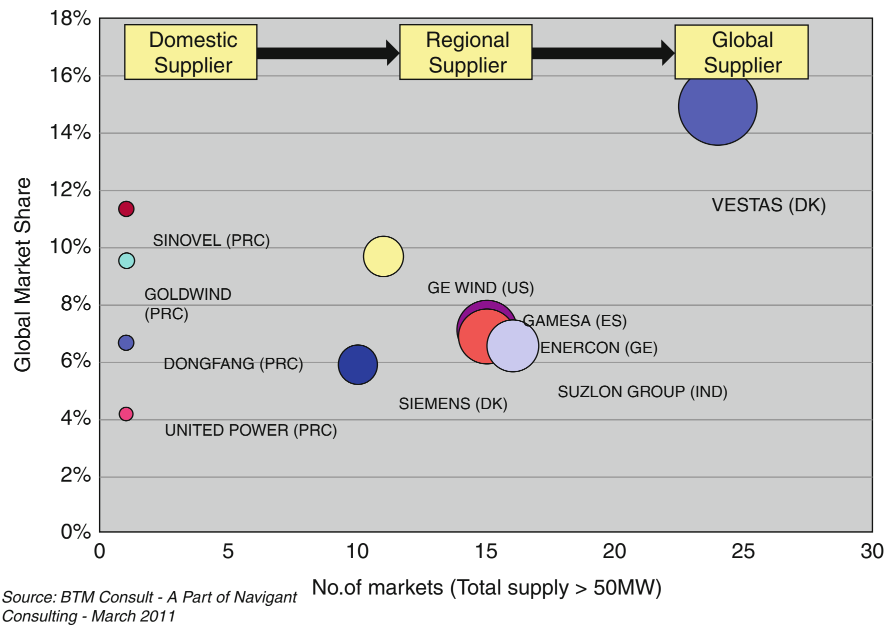


Fig. 57.5 Top 10 wind turbine market share in 2010 (BTM Consult 2010)

4 Environmental Impact of Wind Turbines

Wind turbines have some negative as well as positive impacts on the environment. The possible negative impacts of wind turbines are visual impact, noise, bird and bat kills, shadow effect and pollution during manufacturing and installing the wind turbines, land use, electromagnetic interference, marine mammals, etc. A number of studies have concluded these impacts are minor or easy to avoid (Boyle 2004).

Wind turbines are highly visible elements with rotating blades in the landscape. In flat areas often wind turbines are placed in simple geometrical layout, and in hilly areas better layout is the turbines follow the altitude contours of the landscape. Big wind turbines with low blade rotation speed and similar size and type fit better in the surrounding than bigger number of small turbines with higher rotation speed, in terms of their visual effect as an environmental factor.

In Denmark there are several examples of birds nesting in cages mounted on wind turbine towers. Some birds get accustomed to wind turbines very quickly; others take a somewhat longer time. A number of studies (including offshore wind farms) have concluded that birds almost always modify their migratory routes, but migratory routes of birds should be taken into account when siting wind turbines.

Wind turbines cast a shadow on the neighboring area when the sun is visible. The rotor blades cause a flickering (blinking) effect while the rotor is in motion.

Table 57.2 Emissions avoided using wind farms to produce electricity (Environmental issues 2009)

	Emissions				Benefits		
	Average wind (onshore and offshore)	Hard coal	Lignite	NGCC	vs. coal	vs. lignite	vs. NGCC
CO_2, fossil (g)	8	836	1,060	400	828	1,051	391
SF_6, fossil (mg)	8	2,554	244	993	2,546	236	984
NO_x (mg)	31	1,309	1,041	353	1,278	1,010	322
NMVOC (mg)	6	71	8	129	65	3	123
Particulates (mg)	15	147	711	12	134	693	−6
SO_2 (mg)	32	1,548	3,808	149	1,515	3,777	118

Source: CIEMAT

In Germany the judge tolerated 30 h of shadow flicker per year. Also, there are possibilities of computing a shadow map.

The energy balance of wind energy is very positive. The energy consumed in the whole chain of wind plants is recovered in several average operational months.

Environmental benefits of wind electricity can be assessed in terms of avoided emissions compared to other alternative electricity generation technologies (CO_2, SO_2, NO_x, and other pollutants). Emissions avoided using wind farms to produce electricity instead of coal or natural gas power plants are quantified in Table 57.2 (NGCC – natural gas combined cycle, NMVOC – nonmethane volatile organic compounds). The CO_2 emissions related to the manufacture, installation, and servicing over the average 20-year life cycle of a wind turbine are offset after a mere 3–6 months of operation, resulting in net CO_2 savings thereafter.

Wind energy also avoids significant amounts of external costs of conventional fossil fuel-based electricity generation.

5 Types of Wind Turbines

Windmills, wind turbines, or devices for conversion of wind energy into mechanical work can be classified according to various criteria. The most common is according to:

- Aerodynamics
- Rotor axis position

According to the aerodynamic impact, they can be divided into those using:

- Resistance
- Uplift force
- Combination

One way to classify wind turbines is in terms of the axis around which the turbine blades rotate:

- Horizontal axis wind turbine (HAWT)
- Vertical axis wind turbine (VAWT)

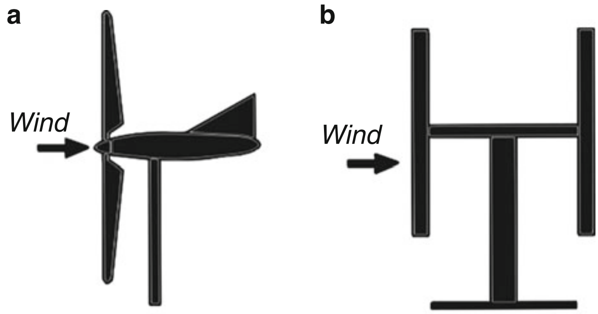


Fig. 57.6 Wind turbines (**a**) HAWT, (**b**) VAWT

Most modern wind turbines are horizontal axis wind turbines of upwind type, Fig. 57.6.

In the recent decades construction development concept of wind turbines, influenced mainly by technological-technical factors, has been developing in several lines (Gasch and Twele). The best concept proved to be the Danish one, or the concept of horizontal three-bladed wind turbine with transmitter-multiplicator. Attempts to apply the wind turbine concept with one- or two-bladed rotor have not been successful so far.

6 Wind Power

Wind turbines transform kinetic wind energy into mechanical work, so it should start from the kinetic energy expression, proportional to the multiplication of mass (m) and squared wind speed (v).

$$E = \frac{1}{2} m v^2 \tag{57.1}$$

Since the power is a product of energy divided by time, it is

$$P_v = \frac{1}{2} \dot{m} v^2 \tag{57.2}$$

Using expression for mass flow rate

$$\dot{m} = \rho v A \tag{57.3}$$

where ρ is air density, A is cross-sectional area, and combining with expression (57.2), it gives an important relationship for wind power:

$$P_v = \frac{1}{2} \rho A v^3 \tag{57.4}$$

Table 57.3 Specific wind power

Wind speed (m/s)	Power (W/m^2)
0	0
1	1
2	5
3	17
4	39
5	77
6	132
7	210
8	314
9	447
10	613
11	815
12	1, 058
13	1, 346
14	1, 681
15	2, 067

For standard meteorological conditions at the temperature of 15°C and the pressure of 1,013.3 hPa, air density is 1,225 kg/m^3. Table 57.3 shows the power per meter of cross section (W/m^2) for different wind speeds, a quantity that is called the specific power or power density.

Kinetic wind energy turns into mechanical work at the rotor blades, which is the result of lowering of the wind speed due to the impact of wind against the rotor level.

It is normal that the entire wind energy cannot be used at the rotor, i.e., air flow cannot be stopped. Thus, in the expression (57.4) the coefficient of power of aerodynamic transformation C_p, it needs to be added, and its value is going to be discussed further:

$$P_v = \frac{1}{2} \rho A v^3 C_p \tag{57.5}$$

7 Aerodynamic Model of a Wind Turbine

Wind turbines use kinetic wind energy for getting of needed power to start an electric power generator. Depending on constructive solutions, there are several types of wind turbines, a horizontal one being the most widely used (rotor axe is parallel to horizontal line).

In theoretical studies of aerodynamic characteristics of wind turbines, the turbine is replaced by an ideal one that represents a circular discontinuous area of pressure. That is the simplest aerodynamic wind turbine model, so-called Rankine-Froude disc model. This model is also known as the actuator disc model. Rotor is shown as a rotating disc with infinite number of immeasurably thin blades whose resistance

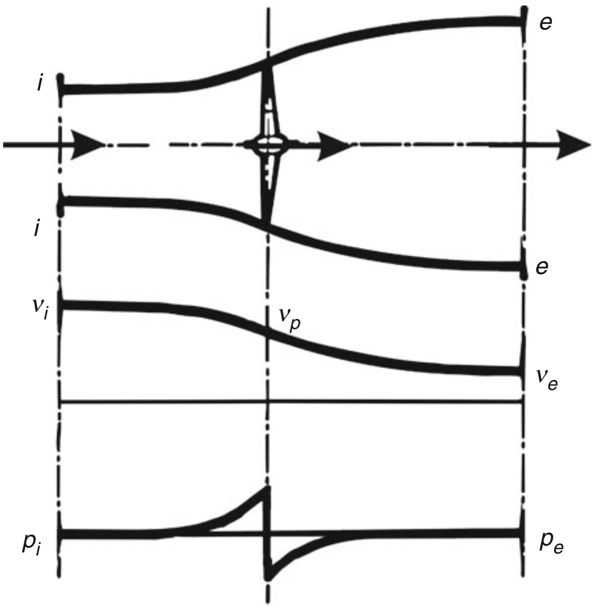


Fig. 57.7 Diagram of streamlines, speeds, and pressures for an idealized wind flow through the wind turbine rotor (Technical Encyclopedia 10 1982)

equals zero and whose tip speed is higher than the wind speed. This model assumes a sudden drop of pressure at the rotor disc. Flow speed is constant in radial direction, changing slowly from the period prior to the blade impact to the one after blade impact. It is calculated that flow speed remains the same beyond the flow boundaries. Thus, an ideal wind turbine is a mathematical discontinuous surface of pressures through which the wind flows at a constant speed, without any friction or whirls.

Figure 57.7 shows a diagram of streamlines, speed, and pressures for idealized airflow through the rotor of a wind turbine with a horizontal axis. External streamlines turn toward edges in the rotor zone, due to obstacles. They go around rotor and do not take part in energy transformation. Sections $i - i$ and $e - e$ are placed far enough from the rotor. The wind power at the rotor is

$$F = \dot{m}\,(v_i - v_e) \tag{57.6}$$

where $\dot{m}$ (kg/s) is a flow of air mass through a control volume, and v_i and v_e(m/s) are wind speeds in the sections $i - i$ and $e - e$. By evening power absorbed by an ideal rotor with change of kinetic wind energy in its flow through the control volume limited by the sections $i - i$ and $e - e$, formula is taken from

$$P = F \times v_p = m\frac{v_i^2 - v_e^2}{2} \tag{57.7}$$

By adding the expression (57.6), it results in

$$\dot{m}\,(v_i - v_e) \times v_p = m\,\frac{v_i^2 - v_e^2}{2} \tag{57.8}$$

where the wind speed at the rotor level is

$$v_p = \frac{v_i + v_e}{2} \tag{57.9}$$

and air mass flow through an ideal rotor is

$$\dot{m} = \rho A v_p \tag{57.10}$$

It can be written as

$$\dot{m} = \rho A \frac{v_i + v_e}{2} \tag{57.11}$$

By adding the expression (57.11) into the expression (57.7), the result is

$$P = \frac{1}{4}\rho A\,(v_i + v_e)(v_i^2 - v_e^2) \tag{57.12}$$

Differentiation of the expression (57.12) through v_e and equaling of $dP/dv_e = 0$ results in a maximum power for $v_i = 3v_e$ so the maximum power which can be gained from the wind is

$$P = \frac{8}{27}\rho\, A\, v_i^3 \tag{57.13}$$

Having the total wind power $P_u = \frac{1}{2}\rho A\, v_i^3$, maximum wind turbine efficiency is

$$C_{p\,\max} = \frac{\frac{8}{27}\rho A\, v_i^3}{\frac{1}{2}\rho A\, v_i^3} = \frac{16}{27} \quad \text{or} \quad 59.3\%$$

This regularity was formulated by the German physicist Albert Betz in 1919, and it called Betz's law which says that a maximum of 59.3% of kinetic wind energy can be turned into mechanical energy. Of course, due to different kinds of losses of wind turbines, this level is lower today and its maximum is 50%.

8 Wind Turbine Parts

The best constructive solution is a lift-based wind turbine with a rotor placed on the front (upwind) side of the tower and which is parallel to the horizontal line, Fig. 57.8. For that reason, mostly this type of turbine will be taken into consideration.

In this section will be discussed. These main parts are:

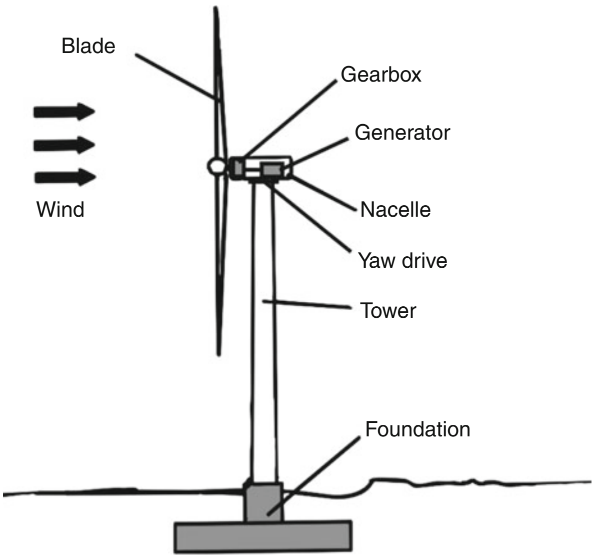


Fig. 57.8 Wind turbine – main parts

- Rotor
- Gearbox
- Generator
- Regulation system
- Tower
- Foundation

Figure 57.8 shows the basic functional parts of a horizontal wind turbine.

Figure 57.9 shows basic components and functional elements of Vestas turbine V90-3.0 MW, and more details on this type can be found in the Table 57.4.

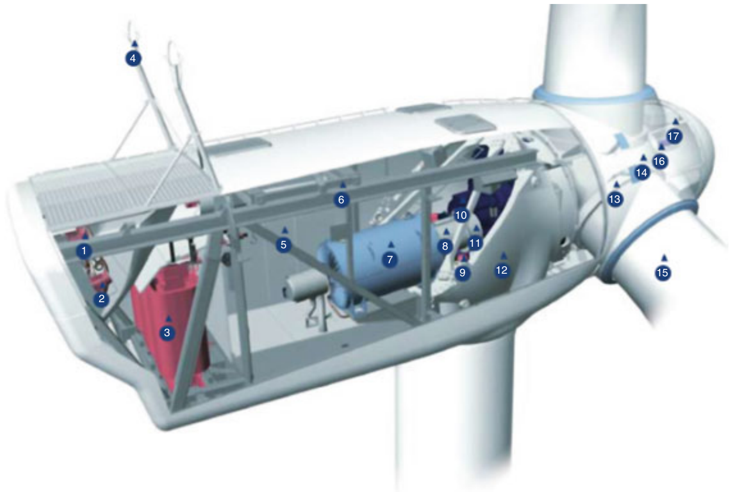
Table 57.4 shows the main characteristics of some types of wind turbines that can be found on the market.

9 Rotor

Wind turbine rotor is made of certain number of blades connected to the shaft through hubs. Rotor speed is one of the main project parameters of any wind turbine. Since the wind turbine power equals a multiplication of rotor torque and rotor speed

$$P = M\Omega = M\,2\pi n, \tag{57.14}$$

it can be concluded that the power will increase with increased force – load on the rotor blade, e.g., higher wind speed and longer rotor diameter. Since the wind



1 Oil cooler
2 Water cooler for generator
3 High voltage transformer
4 Ultrasonic wind sensor
5 VMP-Top controller with converter
6 Service crane
7 OptiSpeed®-generator
8 Composite disc coupling
9 Yaw gears
10 Gearbox
11 Mechanical disc brake
12 Machine foundation
13 Blade bearing
14 Blade hub
15 Blade
16 Pitch cylinder
17 Hub controller

Fig. 57.9 Basic parts of the wind turbine V90-3.0 MW (vestas.com)

speed cannot be affected, longer rotor diameter might be a solution. Limits are technological and mechanical characteristics of equipment and material.

A very significant parameter for aerodynamic designing of rotor blades is tip speed ratio. It represents ratio of the rotor blade tip speed and the wind speed (value of so-called undisturbed streamline):

$$\lambda = \frac{2\pi n R}{v_1} = \frac{\Omega R}{v_1} \tag{57.15}$$

Also, the formula proves that rotor speed can be connected to the tip speed ratio. Wind turbines with a small number of rotation have a low λ (ca 1), with a high start torque. For these reasons it comes to a bigger number of blades and, consequently, a high rotor thrust. A typical example is American windmill with 20–30 blades, Fig. 57.10. Wind turbines with $\lambda = 5 - 8$ have no such problems, and they have just few tall and well-shaped blades. Another reason for usage of rotors with a small

Table 57.4 Characteristics of wind turbines (Wind Turbine Market 2005, 2007, nordex.de)

Type	Enercon E-70	Nordex N80	Repower 5M	Vestas V90/3 MW
Hub height	57/64/85/98/113 m	60/80/100/115 m (lattice)	100/120 m onshore	80/105 m
Rated power (kW)	2,300	2,500	5,000	3,000
Tower construction	Concrete, tubular steel	Conical tubular steel, lattice	Conical tubular steel	Conical tubular steel
Tower weight	140/232/336/1,171 t	115/193/281/205 t		175/275 t
Nacelle weight (t)	66	86	290	70
Cut-in wind speed (m/s)	2.5	4	3.5	4
Rated wind speed (m/s)	13.5	15	13	15
Cut-out wind speed (m/s)	28–34	25	25	25
Rotor blade type	*3 E-70/4*	*LM 38.8/or/NR 40*	*3 LM 61.5*	*RISÖ P + FFA-W3*
Rotor diameter (m)	71	80	126	90
Swept area (m^2)	3,959	5,026	12,469	6,362
Rotor speed (rpm)	6–21.5	10.9–19.1	6.9–12.1	8.6–18.4
Blade tip speed (m/s)	22–80	80	80	75.7
Blade weight (kg)	6,000	8,700	19,000	6,600
Rotor speed control	Variable by MC-System	Variable by MC-System	Variable by MC-System	OptiSpeed™
Overspeed control	Pitch	Pitch	Elec. pitch, independent blade feathering	Pitch

(continued)

Table 57.4 (continued)

Type	Enercon E-70	Nordex N80	Repower 5M	Vestas V90/3 MW
Generator type	*Enercon E-70 E4*	*Winergy*	*Diverse*	*Diverse*
Generator construction	Synchronous, multiple ring generator	Asynchronous, double fed	Asynchronous six-pole, double fed	Double fees asynchronous with wounded rotor and slip rings four-pole, OptiSpeed™
Grid connection	Inverter	2,500 kW	5,000 kW	
Generator potential (V)	400	660	660/950	690
Gearbox type	*Without gear*	*Eickhoff, Winergy*	*Diverse*	*Diverse*
Gearbox construction		Spur, planetary	Spur, planetary	2 planetary + 1 spur stage
Gearbox steps		3	3	3
Gear ratio		1:68.14	ca. 1:97	1:104.5
Security systems	*Fail-safe*	*Multiple redundant*	*Pitch, Fail-safe*	*2*
Main brake system	Feathering of each blade with stand by generator	Feathering of each blade	El.independent blade feathering	Pitch
second brake system	Feathering of each blade with stand by generator	Disc brake	Disc brake	Disc brake
Control	*Enercon (microprocessor)*	*Remote field controller*	*Mita-technik A/S*	*VMP, vestas*
Distance control	Enercon scada	Nordex control	DFÜ	VMP, vestas

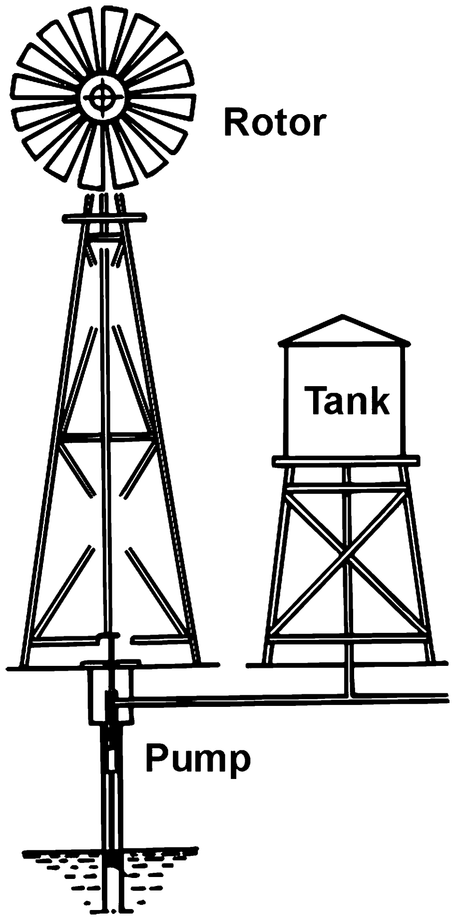


Fig. 57.10 American windmill

number of blades is their high price. Costs of three-blade rotor represent about 20% of total costs of a wind turbine.

Also, sound level is in relation to the tip speed ratio. Number of revolution of a rotor is regulated with a favorable aerodynamic system, which will be also more discussed later.

10 Blades

Basic function of blades is to turn kinetic energy of wind into mechanical work needed for rotation of rotor. Today's blade types are designed aerodynamically so they can be moved by uplift force. The most widely used are three-bladed rotors.

In today's wind turbines, rotor diameter reaches up to 164 m. This results in a lower rotor speed in order to maintain a certain tip speed ratio. Of course, those blade parts closer to the hub will work with a lower coefficient of usability.

Mechanics of fluids proved that one third of the blade length closer to the blade tip will produce two third of power as related to the entire blade, while one third of its length closer to the rotor hub is almost unproductive under nominal conditions, but it also has a function in reaching the start torque.

Blades represent a critical element of wind turbines in relation to dynamic load under conditions of a turbulent fluid flow. Especially critical is the place of metal connection with the rotor hub due to the complexity of links between the blade composite structures and the metal part.

Blade tip speeds reach high values. Three-blade rotors reach blade tip speeds between 70 and 90 m/s.

In designing and implanting wind turbine rotor blades, several requirements have to be met: profile shape, strength, mass, elasticity, and dynamic balance of mass for a maximum number of rotation.

Great help in reaching these goals is provided by computer programs. CFD (computational fluid dynamics) is a group of methods dealing with studies of behavior of airflow about rotor and wind turbine blades.

Material used for blade forms is usually composite materials: polymers (polyester) reinforced with glass or carbon fiber, Kevlar (it has better mechanical characteristics – tensile strength), or epoxy adhesive.

In a blade production process, it is necessary to invest a lot of manual work and attention. A high-quality product is a result of combination of workers' skills and high technology. After production, control and testing are obligatory, on both static and dynamic loads, and modal forms.

11 Gearbox

Gearbox is fixed between the main shaft and the generator. It is one of the most important wind turbine components. Its main function is multiplication of rotation number of the main shaft which does not exceed 100 min^{-1} to the speed required by the generator, which is, depending on the generator type, usually about 1,500 min^{-1}. For different types of wind turbines, there are different transmission relations and different power of gearboxes. The most frequently used are high ratios, such as Vestas V90-3 MW which has the ratio 1:104.5.

Gearbox has been very often a problematic component. Lately it has been given more attention, especially its tribological characteristics, cooling, efficiency, and lower noise level. Special attention is paid to its control (measurement of noise and vibrations).

The two main types of gearboxes are those with cylindrical tooth profiles and planetary ones. Cylindric gearboxes are simple, easier to maintain, and cheaper, while planetary one is compact, produces less noise, and has lower mass and higher efficiency, Fig. 57.11.

Fig. 57.11 Gearbox by "Hansen" company

Today's modern big turbines have mostly combination of planetary and cylindric transmission. The first part is planetary and the other two are cylindric.

Some types of wind turbines (direct drive working at low rotor speeds) have no gearbox.

12 Generator

Electric generator is the most important electric component in wind turbines. It serves to turn kinetic energy of the shaft rotation into electric energy.

Generators for wind turbines are of special design, since they are subject to many changes of rotation torque, due to change of wind speed. It is necessary to cool generators. Recently, attention has been increasingly paid to their quality, i.e., quality of their outgoing power.

Asynchronous and synchronous generators can be used. Both have some advantages and disadvantages.

Synchronous generators have same rotation speed for magnet disc and rotor. They are directly linked to the rotor. Rotation speed depends on the number of poles. By combining rotor rotation speed and number of poles, it can get a certain frequency, e.g., 50 Hz. Thus, a low rotation speed requires big number of poles, which leads to increased dimensions and mass of generators, Fig. 57.12. Bigger dimension results in more labor force and consequently higher cost. Synchronous generator is linked parallel to distribution grid, by means of synchronous devices, which enables connection without electric shock. Its advantages are:

- Enabling an isolated operation with high-quality regulators of power and frequency.
- If overexcited, they might transmit unproductive inductive reactive energy to the grid.

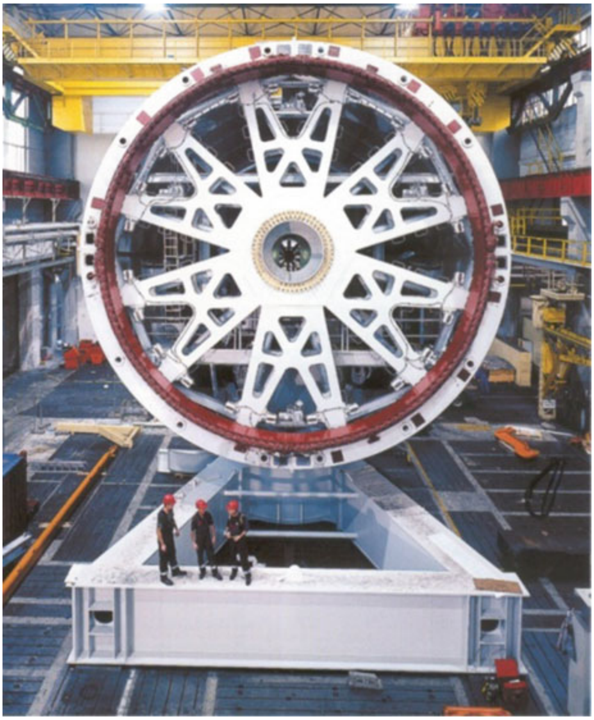


Fig. 57.12 Synchronous generator

Today's turbines use often so-called Danish concept. That implies directly connected asynchronous generator (with cage rotor) to the grid.

Asynchronous generators have different speed of magnet flow rotation and the rotor. The difference in speed represents sliding. That is a very important characteristic since it enables more flexible transmission of the rotation torque and reduces mechanical damage of the teethed transmission. They are connected to the rotor through gearbox. They are often designed in the form of 2 poles and $1{,}500\,\text{min}^{-1}$. Its advantages are:

- Simple primary electric power equipment, since asynchronous generator is not excited and has less demanding cage rotor.
- It has no equipment for excitement and synchronization.
- It uses less demanding equipment for connecting to the grid, as well as protection and program management.

Disadvantages of this generator type are:

- It spends inductive reactive power from the grid or compensation plant.
- Gearbox overloaded.
- It is not suitable for independent running.

Modern wind turbines lately use more and more double-feed wounded rotors. Selection of a certain type of generator for specific wind turbine depends partially on application of desired outgoing characteristics and the cost.

13 Regulating System

Regulating system includes all the wind turbine systems which manage mechanical components. They can be divided into:

- Yawing system
- System for aerodynamic regulation of the rotor speed
- System for mechanical and aerodynamic braking
- Control and management system

Yawing system turns the housing (nacelle) and consequently rotor according to the wind direction, aiming at adjustment of rotor running. Older types of turbines and today's small turbines (battery chargers, etc.) do that by means of rosette or wind vane. Today's huge horizontal wind turbines usually solve that through electric engine or hydraulic transmission whose final teeth is linked with a teethed ring fitted between the housing and the tower (transmission ratio is high and reaches a value of up to 4,000). This system prevents sudden turns of housing in a situation of quickly changing wind directions.

Based on the data measured at the met station on the top of the housing, controller orders turning of the housing (at the speed of ca 1°/s) for a given angle in relation to the horizontal line. The housing is stopped in a needed position, thanks to specially designed brakes.

In case of high wind speed, dangerous for some components or the entire wind turbine, this system is used for braking, together with the whole system for aerodynamic regulation of speed of the rotor revolving.

System for aerodynamic regulation of the rotor speed. Wind turbines are designed to provide a maximum (nominal) power at the wind speeds of about 15 m/s (depending of the type and producers). Wind turbine designer designs it for these speeds since high wind speeds are rare and can damage turbine structure. That means that a favorable system of regulation needs to solve rotor speed as well.

System for aerodynamic regulation of rotor speed (power) can be designed in two ways:

- Passive control (stall)
- Active control (pitch, active stall)

Both principles have pros and contras. In regulation by passive stall, blades are fastened with screws to the rotor hub. At higher wind speed, the angle of attack of the wind is increased, which further causes turbulence and reduction of lift force and increase of resistance, Fig. 57.13. All this leads towards decreasing rotation torque and power.

Advantages of this system are:

- Simpler system without movable parts and complex control systems
- Lower price

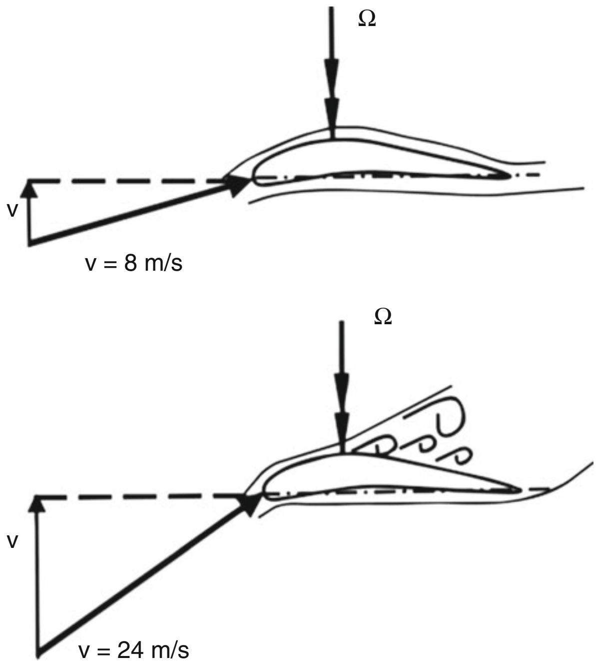


Fig. 57.13 Stall effect

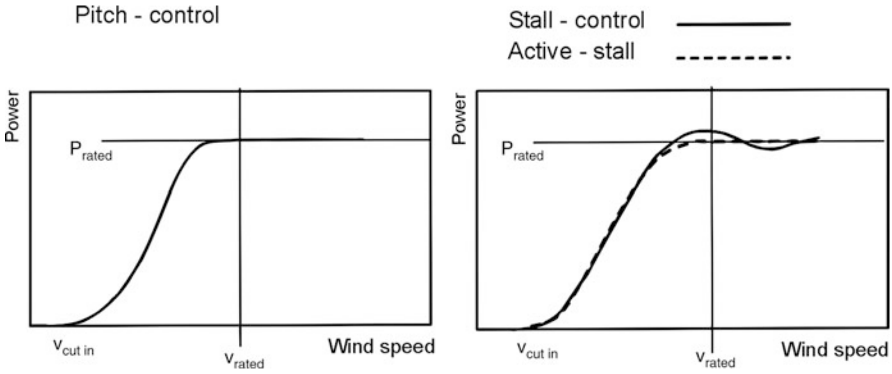


Fig. 57.14 Different power control

Disadvantages are:

- In some cases too heavy dynamic thrust on the rotor due to aerodynamic forces.
- Less usable nominal turbine power. Power starts to decrease slowly when it reaches its nominal value. It is impossible to sustain a stable output, Fig. 57.14.

Today this system is used for low-power (small size) turbines.

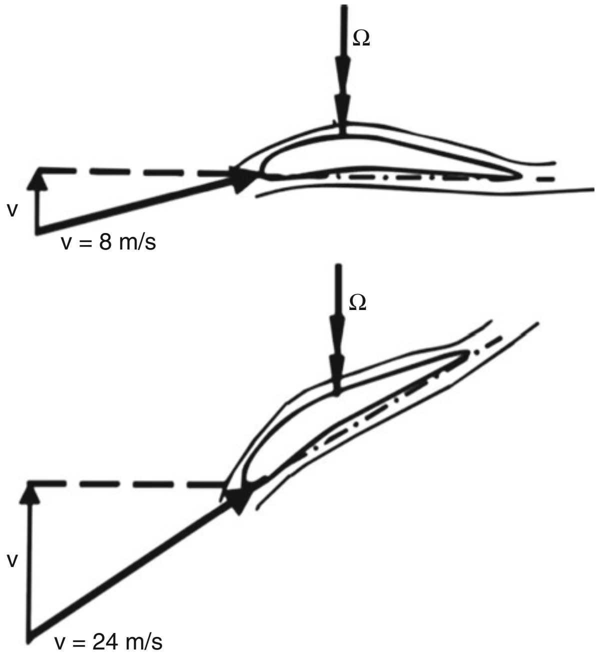


Fig. 57.15 Effect of blade pitching

Regulation with turning of blades has two ways: pitch and active stall. The entire blade turns around its axis for a certain angle, depending on the wind speed, Fig. 57.15. At the high wind speed, blades turn so that wind attack increases, which decreases aerodynamic forces on the blades and consequently on the wind turbine rotor.

Pitch mechanism driven by hydraulic engine will perform turning of the rotor blade to a desirable angle, depending on the wind direction change, in order to maximize output for a specific speed.

In addition to adjustment of speed, the system can serve to stop the rotation, by bringing blades into a position where flow breaks down on the back side of blades.

Basic advantages are less loaded rotor, Fig. 57.16, which leads to a possibility to reduce material and mass in the basic structure. This system is also more flexible and efficient as compared to the stall regulation. Its disadvantage is high cost and possible stalls (special design of the shaft, hub, bearings, etc.)

The first generation of pitch regulation had a central system for simultaneous turning of all blades. For the reason of different wind speeds at different heights and consequently different loads, possibility of turning of each blade separately has been introduced later. Along with other improvements, better usability is obtained, safety, etc.

Active stall regulation is increasingly used in today's big megawatt turbines, Fig. 57.17. It is like pitch regulation, since blades turn around their longitude axis

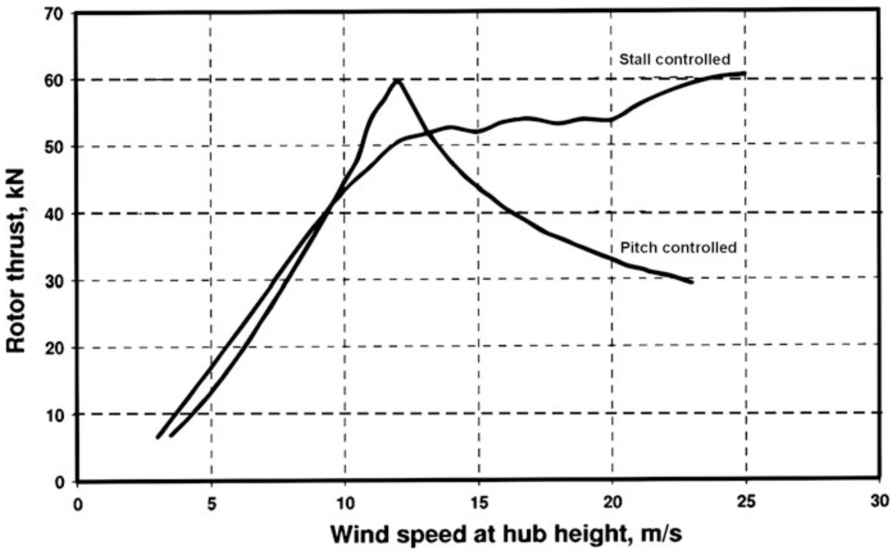


Fig. 57.16 Rotor thrust for different systems of power control

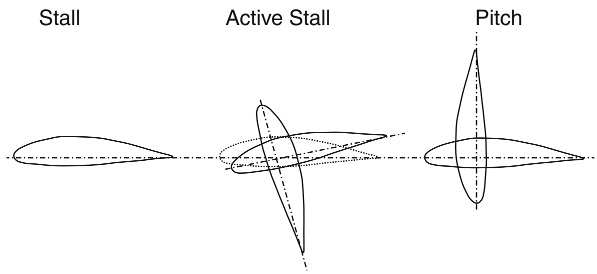


Fig. 57.17 Different principles of power controls

too. At low wind speed, in this regulation, blade turns around its axis just like in pitch regulation. When a set power is reached, the blade starts turning in the opposite direction in comparison to pitch regulation. This form of regulation enables more precise regulation than in pitch, and it is simpler and avoids some aerodynamic problems that appear in pitch regulation.

System of Mechanical and Aerodynamic Braking. System of mechanical braking represents an obligatory component of wind turbines. It has disc brakes hydraulically driven. They are fixed at the generator shaft, because of its lower torque at the teeth and its turning mechanism.

In addition to mechanical braking, there are aerodynamic brakes in rotor blades. Blades which have pitch regulation system, it functions as an aerodynamic brake by means of slow (gradual) increase of resistance force and decreased torque.

Control and management system aims at maintaining the turbine within an operating range, i.e., it regulates and controls internal components of a wind turbine and connects them with external systems. That means limiting of rotor speed, torque, power, and rotor thrust, which is especially related to high-speed wind.

The system processes all the data needed for wind turbine operating (wind speed, wind direction, cooling device temperature, air humidity, rotor thrust, various control signals, etc.) and sends the signals to the central processing unit which manages components of all regulation systems.

14 Tower

Tower is the most massive and after rotor the biggest component of a wind turbine. In the course of time and development of turbines, various mast and tower types have been tested. Tower of horizontal wind turbine is usually tubular and conic in structure, in order to increase its bearing capacity and reduce material cost. Tubular towers have a low aerodynamic resistance, maintenance is simple, they are tall and elegant, and their mounting is quick and simple. They are made of steel and concrete.

A less common structure is lattice. Recently tubular structures are made in several segments, for easier transport and technical conditions of mounting.

Electrical wiring is placed inside the tower, as well as stairs and lift to the housing, controlling units, steering device, measuring equipment, and safety installation.

Conic tubes are made of steel panels of 40–20 mm thickness and different widths. After cutting of steel sheets, roll machine makes tubular shape and these sections are welded by using powder welding technique. After that, welded sections are connected by circular welding into bigger sections of 20–30 m and mass of up to 70 t, Fig. 57.18.

Fig. 57.18 Transport of tower segments

What follows is an ultrasound and x-ray control of the welded points, anti-corrosion protection, and trial assembling section at the locality of the manufacturing plant. Then these sections are transported to the locality, mounted by cranes and joined with bolts.

For a Vestas turbine of V90-3.0 MW, the height of the tower is 105 m, weight of 285 t, and tower diameter of 3.98–2.3 m. Tower has a significant economic share in wind turbines. About 20% of the total price goes to the tower, and for towers higher than 50 m, additional $15,000 is calculated for every additional 10 m. Its height depends on wind characteristics at the locality and of the rotor dimensions. When selecting tower height, it is necessary to determine an optimum solution as compared to the price and outgoing characteristics of electric power from a certain turbine type.

15 Foundation

The main tasks of the foundation are:

- Ensuring stability, i.e., preventing overthrowing of the entire turbine structure
- Maintaining certain limiting values of specific load forces on the ground

For example, for the wind turbines (Vestas 2 MW, rotor diameter 80 m, tower height 100 m) in the area of Steinberg (Austria) are based on the dimensions 15.35 × 15.35 × 1.9 m, Fig. 57.19. The favorable geological structure enables cheaper foundation construction.

Fig. 57.19 Foundation

16 Specific Features of Research

Because of the need to install wind farms on complex terrains and in specific wind conditions, there is a requirement to have special research in these circumstances and consequently, a special analysis of behavior of the selected equipment in these conditions.

There is currently an intensive work under way on new construction designs, for example, the new offshore wind turbine of the company "Vestas" V164 7 MW, which has a 164 m diameter rotor, which means that it has a size almost like three football fields (vestas.com).

"Direct drive" wind turbines present another special example; their biggest manufacturer is German "Enercon." Their program also includes the development of a prototype of machine of 7.5 MW with rotor diameter of 127 m, hub height of 135 m, rotational speed of 5–11.7 rpm, and storm control of 28–34 m/s (enercon.de). It should mention and projects as Sway Turbine AS, 10 MW, (swayturbine.no), Windtec SeaTitan, 10 MW, (windtec.at), etc.

One of the possible solutions that has been subject of intensive work in the past years is a shrouded wind turbine, in Fig. 57.20 (flickr.com), that would be much more efficient than the present "conventional" wind turbines. Either way, it will certainly take a number of years before the new construction designs are put to commercial production.

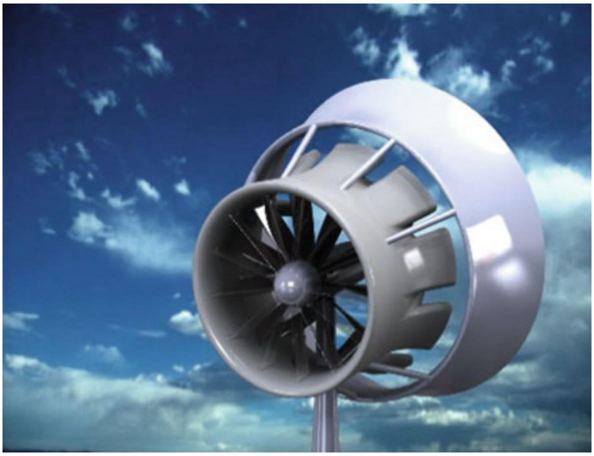


Fig. 57.20 Shrouded wind turbine (flicer.com) (flickr.com)

17 Case Study

An example for case study is Tauernwindfarm Oberzering located in the Austrian Alpine region. Tauernwindfarm is the highest located wind farm in the world (1,900 m above the sea level). Tauernwindfarm Oberzering has 11 wind turbines Vestas V66 1.75 MW with total 19.25 MW (http://www.tauernwind.com). Average wind speed in hub height is 7 m/s, average power density of the wind is 472 W/m^2, and full load is 2,150 h/year. Electricity production is about 40,000 MWh/year (approx. 10,690 households); therefore, efficiency is roughly 24%. Environmental benefits are savings in oil 11.1 million liter and CO_2 reduction 29,900 t/year.

18 Economic Analysis

Wind turbine economics are changing rapidly, because of the new turbine producers, expansion of wind energy, initiatives for RES, etc. Wind turbine economics contains costs and incomes.

- Costs:
  - Pre-investment costs
  - Investment (capital) costs
  - Operation and maintenance (O and M) costs
  - Dismantling costs

Pre-investing costs embrace wind potential assessment, technical project development, economic project development, feasibility study including wind speed measurements, turbine selection, and financing.

Investment costs embrace project development, area, financing costs, contract preparation, wind turbines, grid connection, roads, foundations, cranes for turbine eraction, installation, and commissioning.

Income in wind park projects:

- Payments for production
- Insurances
  - Service interruption
  - Break of machinery
- Guarantee payments
  - Power curve
  - Production guarantees
  - Availability

The main incomes are payments for production of electricity of wind park. Production of wind park depends of wind potential (assessment, long-term behavior), power curve of wind turbines (contract, surveillance), and availability of wind turbines in wind park (contract, surveillance, fast service), Fig. 57.21. The quality of the contracts determines the economy of the whole project.

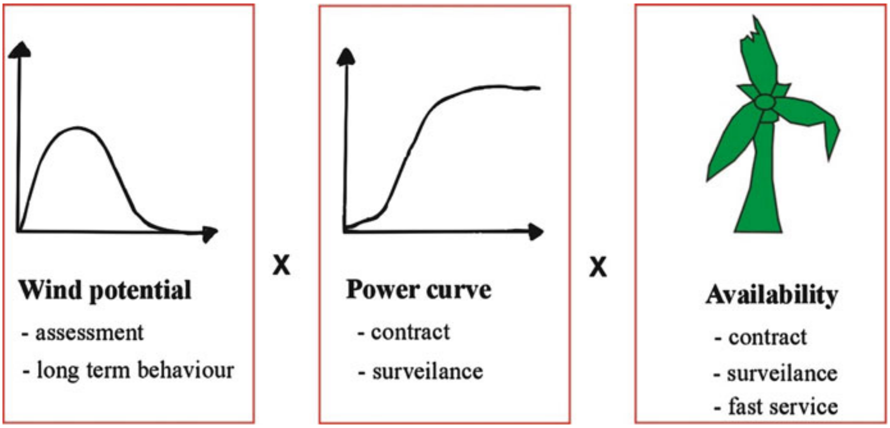


Fig. 57.21 Production of wind park

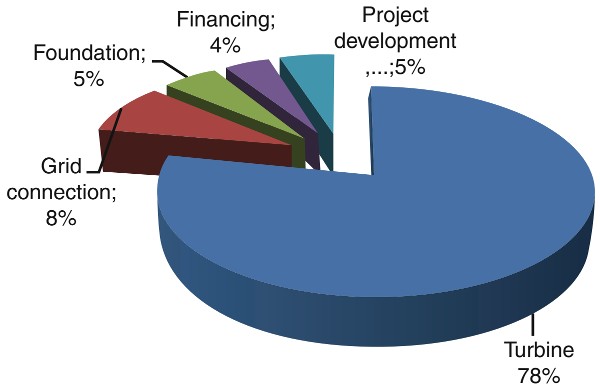


Fig. 57.22 Capital costs of wind park

Central critical points of some wind turbine project are:

- Turbine purchase contract
- Financing
- Liquidity
- Wind turbine repair
- Annual variations of wind climate

Also, other factors affect the economics of wind farm, including depreciation, income taxes, and initiatives.

Investment (capital) costs

Total investment cost is typically 1,100–1,350€/kW (Krohn et al. 2009). It depends from area to area and from country to country. The average structure of investment costs is shown in Fig. 57.22. About 3/4 of the capital cost is cost of wind turbines.

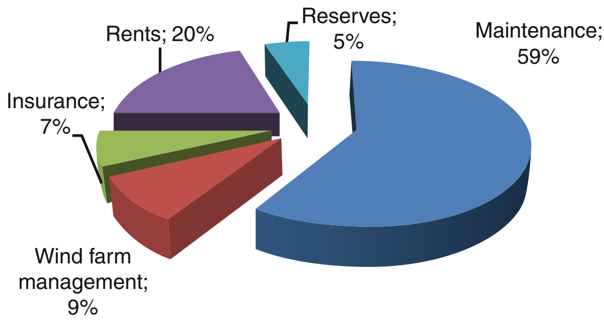


Fig. 57.23 O and M costs of wind park

Operation and maintenance (O and M) costs. O and M costs are:

- Area rental
- Maintenance
- Repair
- Wind farm operation and management
- Insurances
- Interest and clearance for loans
- Taxes

Example of the structure of operation and maintenance (O and M) costs is shown in Fig. 57.23.

Some of operations and maintenance costs (O and M) are annual costs, which do not depend so much on the hours of operation of wind park – annual energy produced – as insurance and administrations, while repairs are directly related to annual energy produced. O and M costs, which have already been levelized to increase future cost escalations, are about 3% of the initial capital cost of the wind farm or approx. 25% of annual income. O and M costs depend on how much the wind park is used in a given year, also on the age of turbines in wind park. According to manufacturers the life span of wind turbines amounts to 25 years. Site specific factors (wind speed, storms, turbulence, icing conditions) and the quality of the maintenance of the turbine have an important influences on life span.

An example cost analysis for Tauernwindfarm Oberzering is given in Table 57.5. In the table are investment (capital) costs and estimate of the levelized annual cost of operation and maintenance (O and M). And Feed-in tariff is 7.8 €ct/kWh for 13 years.

Total capital costs are 23,864,166 €, Table 57.5, and they provided through equity capital 3,650,000 € fundings 2,583,073 € and long-term credits 17,631,093 €. Specific investments are 1,239,696 €/MW, and specific O and M costs 21.23 €/MWh.

It is noteworthy here that it is very difficult to make a comparison between different technologies for generation of electricity, especially these from RES and the "conventional" ones. Nevertheless, it can be concluded that the price of electricity generated from wind farms becomes more and more comparable with the

Table 57.5 An example cost analysis

Capital costs	Amount (€)	Percentage (%)
Wind turbines and accessories	16,915,206	71.0
Legal rights and contract payments	1,541,960	6.4
Electrical cables and grid connection	3,910,000	16.4
Access road incl. surveyor work	605,000	2.5
Public relations, lawyer, and other costs	377,000	1.5
Planning and supervision of construction	515,000	2.2
Total capital cost	*23,864,166*	*100*
O and M costs		
Machine parts, maintenance, and repairs	474,650	54
Personnel costs	106,000	12.0
Administration	40,000	4.55
Property leases	43,000	4.9
Bookkeeping, consultation, and other services	35,000	4
Insurance	140,000	16
Other	40,000	4.55
Total operational costs for 1 year	*878,650*	*100*

price of electrical energy produced from "conventional" fossil fuels. However, the only cases where they are completely comparable are the very large wind parks that are located at places with excellent wind characteristics. For offshore wind parks there is not yet sufficient statistical data. Hence, wind energy projects still need some financial help (incentives) to come up with market prices, and many governments provide incentives for wind-produced electricity (kWh). Wind energy has low contribution of greenhouse gas emission and air pollution, and wind-generated electricity has a benefit for neutralizing the environmental impact. Also, other important arguments in favor of wind energy are the industry's job creation potential and the security of supply.

Figure 57.24 shows average values of the price of electricity produced in wind farms during the period 1999–2010. As presented in the diagram in Fig. 57.24, the data relate to a different number of projects (from 11 to 232) and different number of installed capacities (from 594 to 17,033 MW).

The rated power of new wind turbines is increased. It means the corresponding capital cost per kW dropped. The labor required for new (larger) wind turbine is not much higher than for a smaller one. The cost of a rotor is proportional to diameter as well as power delivered. Also, taller towers of wind turbine increase energy faster than cost increase, etc. But, due to the intensifying installation of wind farms, lower wind speed sites, the use of state-of-the-art technology in the past few years, discussed above in this chapter and other factors, at the beginning of 2006, the wind turbines got even more expensive, which, due to the big influence on the overall cost, also increased the cost of electricity produced in wind parks, Fig. 57.24.

It is difficult to make a realistic forecast of the movement of prices in the future period for the wind farms, as this involves many influencing factors; it is especially difficult to make their comparison with fossil fuels. However, there are a lot of such

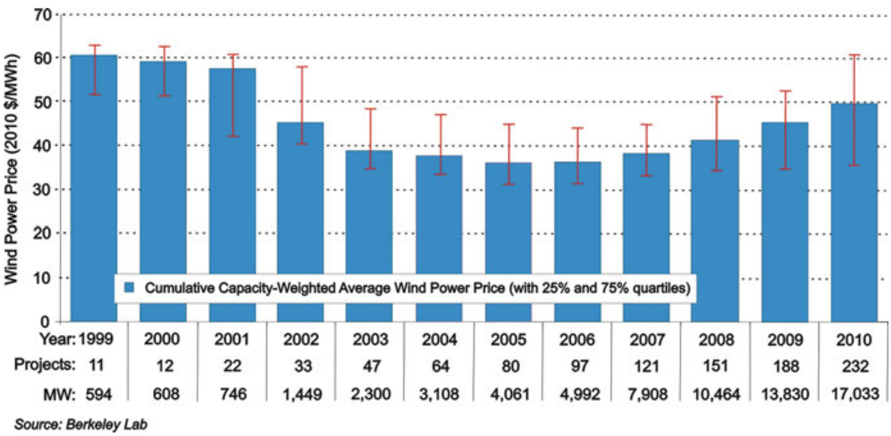


Fig. 57.24 Cumulative capacity-weighted average wind power prices (2010 Wind Technologies Market Report)

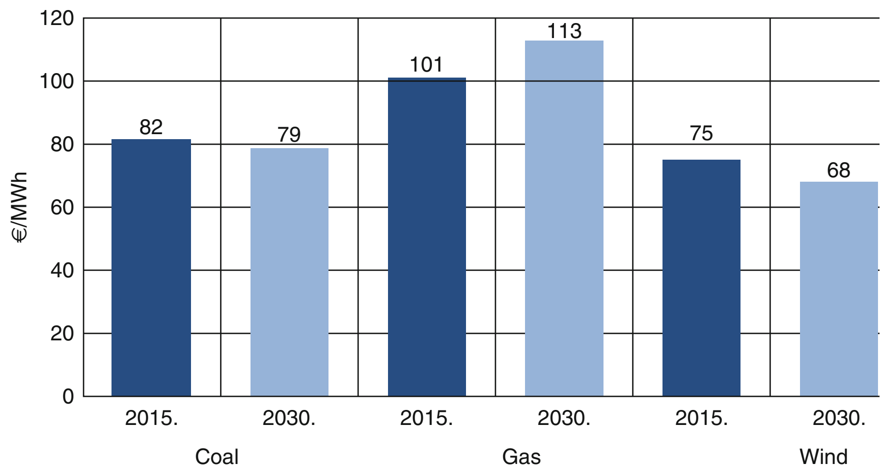


Fig. 57.25 Electricity generating cost in the EU, 2015 and 2030 (Krohn et al. 2009)

forecasts that are more than optimistic (Van Kuik et al. 2006; World Energy Outlook 2009; International Energy Outlook 2010).

IEA in its review from 2008 assumed price increase of constructive costs of the newly built plants in EU. The assumed price of emission is \$30/t of CO_2 plus \$30/MWh of production costs for coal-based plants, while for gas-based plants the cost is \$15/MWh.

Figure 57.25 shows prognoses for electric power production costs in EU for 2015 and 2030 (source: IEA World Energy Outlook 2008). The diagram shows that new capacities of wind turbines in the period 2015–2030 are expected to have lower production price in comparison to the coal and gas technologies.

19 Summary

Wind turbines have their extreme growth and development. In 5 years (2007–2011) the capacities have more than tripled. With the development of technology, technical characteristics of wind turbines and wind parks have significantly improved. There is currently an intensive work underway on new construction designs.

Wind turbine economics are changing rapidly, because of the new turbine producers, expansion of wind energy, initiatives for RES, etc. The generation cost of wind turbines approaches the cost of coal-fired generation.

Wind turbines have some negative as well as positive impacts on the environment. Benefits of wind energy are different and very important. Experience in the implementation of wind projects in the EU shows that social acceptance is very important for the successful development of wind energy.

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