Chapter IV

Wind Energy

1. Wind as energy source

Wind energy has been used by mankind over thousands of years. For over 3000 years the windmills have been used for pumping water or grinding (milling). And nowadays, in the century of information technologies, nuclear energy and electricity, thousands of windmills are used for pumping water and oil, for irrigation and production of mechanical energy to drive low-power mechanisms on different continents.

Electricity can be obtained using different methods, but absolutely all require fuel, in most cases fossil fuels - coal, natural gas, oil or uranium 235 and plutonium 239 in thermonuclear plants. By burning or nuclear fission the primary energy embedded in the fuel is converted into thermal energy (heat). The turbine, designed specifically for each type of fuel, drives the generator that produces electricity. In this context, the electricity produced from the wind is not differing from the electricity produced from fossil or nuclear fuels. The wind as a fuel is essentially different – it is free of charge and does not pollute the environment.

Nowadays, the phrase "*use of wind energy*" means, primarily non-pollutant electrical energy produced at a significant scale by modern *"windmills"* called *wind turbines*, a term that attempts to outline their similarity to steam or gas turbines, which are used for producing electricity, and also to make a distinction between their old and new destination.

The attempts to obtain electricity from the wind date back over a hundred years since the late nineteenth century. But a true flourishing of this technology is registered only after the 1973 oil crisis. An unexpected increase in oil prices has forced the governments of developed countries to allocate substantial financial resources for research, development and demonstration programmes. Over 20 years, worldwide, a new technology, a new industry and, in fact, a new market - the market of the Wind Energy Conversion Systems (WECS), have been developed.

If in 1973 the main incentive for the development of WECS was the oil price, today another incentive is added - the tendency of mankind to produce "*clean*" or "*green*" electricity with little or no carbon monoxide emissions. The year 1993 was marked as the beginning of a wind boom characterized by an annual increase of over 20% of installed power capacity. Thus, in 1999 the global capacity increased by 4033 MW, which was a record for the wind energy sector. It is rather significant as it exceeded the world installed nuclear power capacity in the same year, for the first time [1-3]. In the period 2001-2011 the global capacity has increased than 10 times and has reached 238 MW in 2011 (Figure 4.1) [4,5].

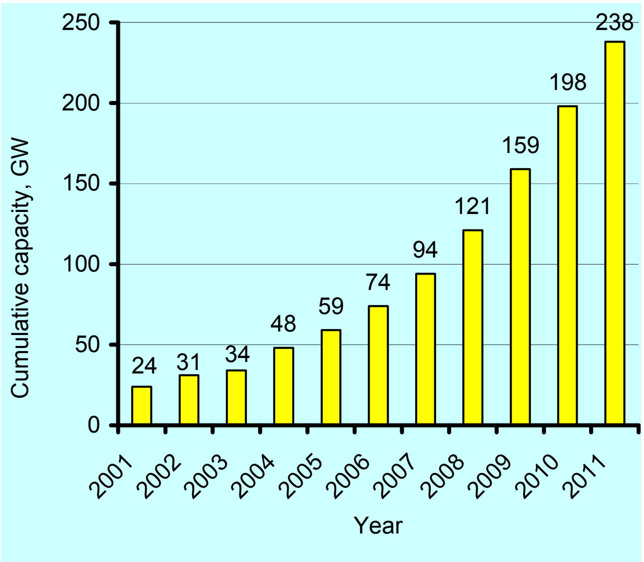


Fig. 4.1. Installed cumulative wind capacity

The global leader is the European Community EU-27 with a 39,5% share, followed by China, the USA and India (Fig. 4.2). Such a spectacular development knows no other global industry sector worldwide. In the years 2007-2011 an annual growth over 25 % was expected; for 2011 the global installed capacity have reached 238 000 MW. With the launch of the European Technology Platform on wind energy issues the EU Commissioner A. Piebalgs said [6]: *"Wind energy technology is certainly one of the fastest growing and plays an important role, contributing to create a sustainable and competitive energy policy in Europe"*. In 2011, in the EU countries about 5 % of the electricity consumed was produced from wind. The wind provides electricity to more than 50 million households in the EU, but very few know it – a symptom which indicates a lack of knowledge about this technology. Globally, by 2020 about 12% of the produced electricity will be of wind origin. Table 4.1 lists the most advanced five countries and five global companies in the field of the wind energy.

To know the whole technology of the wind energy conversion into electricity, knowledge in various fields is required, including meteorology, aerodynamics, electrical engineering, mechanical engineering and civil engineering. In order to make a correct decision for investment it is necessary to have knowledge of the economic analysis of projects.

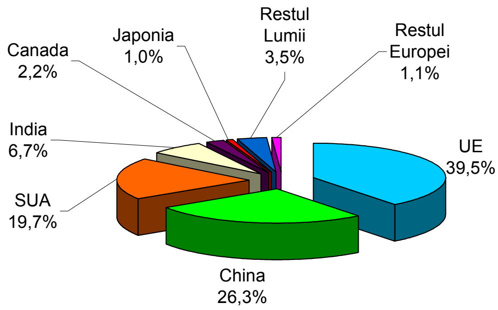


Fig. 4.2. Distribution of installed wind power at global level

The following chapter describes the principle of converting the kinetic energy of an air stream into mechanical energy, the formulas for calculating the airflow power and the technical limitations are presented, which reduce the conversion efficiency. Then, a review of the wind technology developments, the major construction schemes, modern trends in

Table 4.1. World most advanced countries and companies in the wind technology.

Country	Installed wind power, MW	World share, %	Company	Wind market share, %
China	62733	26,3	Vestas, Denmark	12,9
SUA	46919	19,7	Goldwind, China	9,4
Germania	29075	12,2	GE Wind, USA	8,8
Spania	21 673	9,1	Gamesa, Spain	8,2
India	16984	6,7	Enercon, Germany	7,9

the construction of wind turbines and the use of materials for blades are presented. The technical characteristics of high power turbines are presented, including the turbines suitable for use in the wind conditions of Moldova and the steps needed to be done at the initial phase of a wind power plant construction. The last paragraph describes low-power turbines, including the elaborations drawn by the authors and examples of their rational application.

2. Estimation of the wind energy resources

2.1. Characteristics and parameters of the wind energy

Wind serves as "*fuel*" for wind power plants. Taking into account that the wind power density (see p. 4.1) is proportional to the cube of the wind speed it is very important to know the wind energy resources over the whole country, the wind sources of the region and the site where possibly the wind power plant will be built. Typically, the wind energy resources are explained by two main characteristics of the wind – the wind speed and its power density, which determines the wind energy potential of the location.

For policy makers at central level, it is important to know the wind energy resources for strategic planning; in this regard the following questions should be answered [7]:

- What are the wind energy resources and how are they spread across the regions?
- What is the share from the total electricity consumption that can be covered by the wind energy?
- How can we exploit this potential?

At the local level or for an investor in the wind energy at the initial stage of implementing a project, it is important to know the answers to the following questions:

- What is the wind energy potential on a certain site?
- How much electricity will be produced in one year by a turbine with specified technical characteristics?
- What will the cost price of wind power be?
- What is the period of return on investments?
- What is the annual and diurnal variation of the wind speed, and respectively, of the wind power density?

The correct answers can be obtained as a result of measurements of wind characteristics at the given site at the height of the turbine axis of rotation for a minimum of one year period. But this way is expensive and requires a long period of time.

Countries with a high degree of wind energy use have chosen a different way - computer modelling of the wind speed for large areas, using special software that would consider the orography and the land surface characteristics, the obstacles, etc. In these models, the so-called historical wind data is applied collected from the weather stations across the country or region. As a result, the Wind Atlas (WA) is developed, which includes information about the speed and wind power density in the form of a contour or graded map. The Wind Atlas can be produced at a global, country or region level, but it does not substitute the need for instrumental measurements; it only identifies the region where to focus investigations and to indicate the location where necessary to perform the measurements.

At the next phase of investigations, a virtual wind turbine with known technical characteristics may be located in a certain geographical point and, using the WA data, it can determine the amount of electricity that can be produced in a certain period - a month or a year, etc. Obviously, there are constraints that limit or make it difficult to use mathematical models to estimate the wind energy resources. First of all, we refer to the availability of reliable primary data on wind and digital topographic maps for the scale required. No less important is the availability of wind data measurement characteristics - speed and direction, carried out at least 50 m height above the ground in order to validate the results obtained by calculation.

The **wind speed and direction** are the main characteristics of wind for a certain location. At meteorological stations the wind speed is measured by cup anemometers, which are also fitted with wind vanes to determine the wind direction. According to the standards, the wind speeds have been obtained as a result of every three hours records, respectively, at 0, 3, 6, 9, 12, 15, 18, 21 o'clock. The wind speed for each three hours interval is considered the average fixed velocity for an interval of 10 minutes, i.e. between 0^{00}-0^{10}, 3^{00} -3^{10}, etc. The weather stations measure wind characteristics at a height of 10-12 m above the ground.

The wind is characterized by a pronounced change in both its speed and direction and, in order to obtain accurate information, the primary data for a minimum period of 10 years is necessary. Figure 4.3 shows an example of the variation in the wind speed over a period of 24 hours, at a height of 50 m above the ground. The diagram shows the processed results of the wind speed collected every 3 seconds. As a result of the speed measurement, the average speed over a period of time equal to 10 minutes (the arithmetic average of 200 measurements) is considered. Thus, we will have 144 results in 24 hours. We state that the average wind speed for 10 minute intervals varies in 24 hours from 0 to 8,71 m/s.

Obviously, we can determine the average speed for an interval bigger than 10 minutes, for example, for an hour, a day, a month or even for a year. But the information about the average wind speed for a certain interval is not sufficient to consider the potential of the wind energy. To demonstrate this assertion, we calculate the average wind power density for the above example, i.e. for a period of 24 h.

Average wind power density. It is measured in W/m^2 and characterizes the wind energy potential of the location. Average arithmetic speed in the example above, within 24 h is equal to 4,49 m/s (see the line *parallel* with x-axis in Figure 4.3). Using formula (4.9), we obtain the average wind power density

$$p = 0{,}5\rho V^3 = 0{,}5 \cdot 1{,}225 \cdot 4{,}49^3 = 54{,}5 \text{ W/m}^2,$$

where ρ is the air (atmospheric) density; V is the average wind velocity.

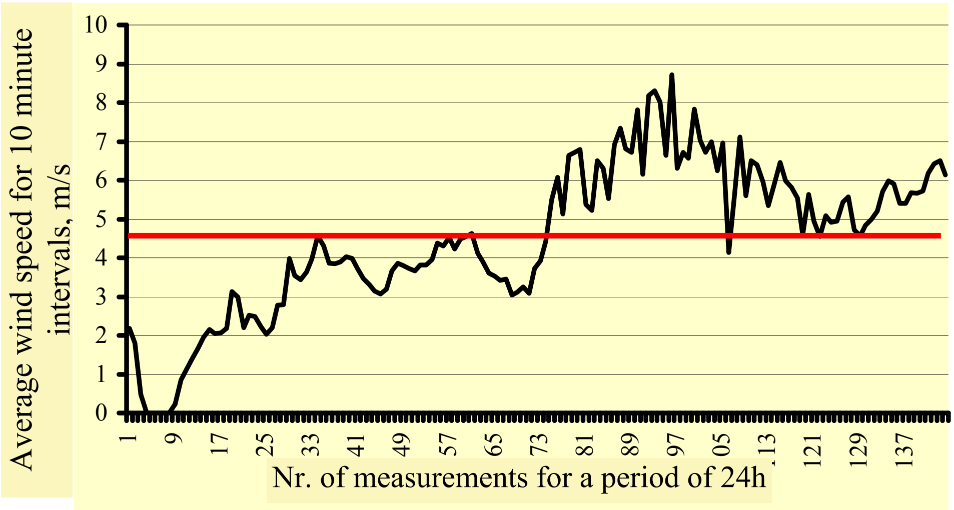


Fig. 4.3. An example of wind variation for 24 hours.

But the wind velocity is a variate and it should be characterised in terms of probability theory. Such a term is the probability density function of the wind velocity, *F (V),* which is defined as the fraction of time for which the average wind velocity falls within a specified interval ΔV_i. In other words, the probability density function of the wind velocity characterizes the share of velocity in the range of V_{min} and V_{max} obtained during the measurements. To determine the probability density function of the wind velocity for the example above (Figure 4.3), let us proceed as follows:

- the velocity variation range during the measurements is determined. In our case V_{min} = 0,0 and V_{max} = 8,71 m/s;
- The velocity variation range is divided into *n* equal intervals, usually between 0,1 and 1,0 m/s. It was chosen ΔV_i = 1,0 m/s. The speed of calculation for each period is equal to the average velocity. For example, within the interval 6 velocities between 5 and 6 m/s are enclosed, the average speed of calculation is considered equal to 5,5 m/s;

- 144 measurements are scanned and the number of measurements n_i is determined falling in each interval;
- function $F(V)= n_i/ N \cdot\Delta V_i$.is determined.

The obtained results have been included in table 4.2 and Fig. 4.4 (the histogram or the bar chart).

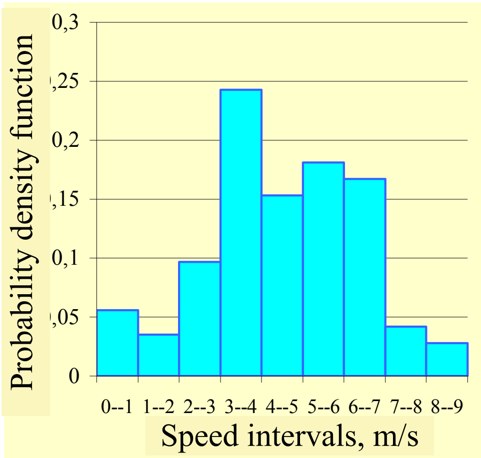


Fig. 4.4. Velocity probability density function.

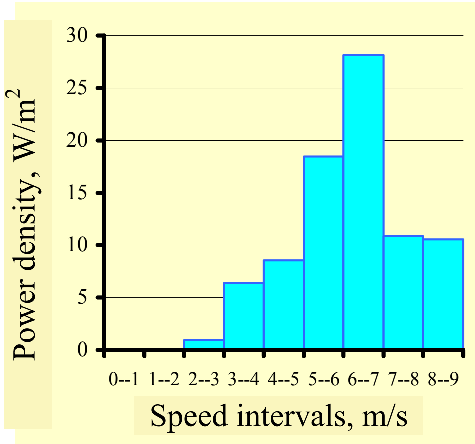


Fig. 4.5. Wind power density.

By considering the probabilistic nature of the wind velocity, the power density is calculated by formula

$$p = 0{,}5\rho\sum_{i=1}^{9} V_i^3 F(V_i) = 83{,}9 \text{ W/m}^2 \qquad (4.1)$$

and is 54% higher than the power density calculated above, using only the average wind velocity for 24 h. Graphical interpretation of results is shown in Fig. 4.5. The largest rate of power density belongs to the velocity range between 6 and 7 m/s and is 35,5%. However, the highest rate of velocity belongs to the speed range between 3 and 4 m/s (see Figure 4.4). Modern turbine start-up speed is equal to or bigger than 4 m/s. From Figure 4.4 it results that, for the analyzed period (24 h), the lucrative velocities duration (≥ 4 m/s) is about 60%.

Turbulence. It refers to fluctuations in the wind velocities over a short period of time, usually less than 10 min. Turbulence is caused by two phenomena: first, the friction between the airflow and the Earth surface, often magnified by topographical features, such as valleys, hills and mountains; the second is related to thermal effects which cause vertical movement of air masses.

Turbulence has a negative influence on the turbine rotor, as mechanical stress caused by short gusts of wind increases, the material from which the propeller is made exhausts and it may fail. Simultaneously with height increasing, the turbulence is reduced. One of the indicators characterizing the turbulence is turbulence intensity defined as the ratio of standard deviation σ and the average velocity for a period of time equal to or less than 10 minutes.

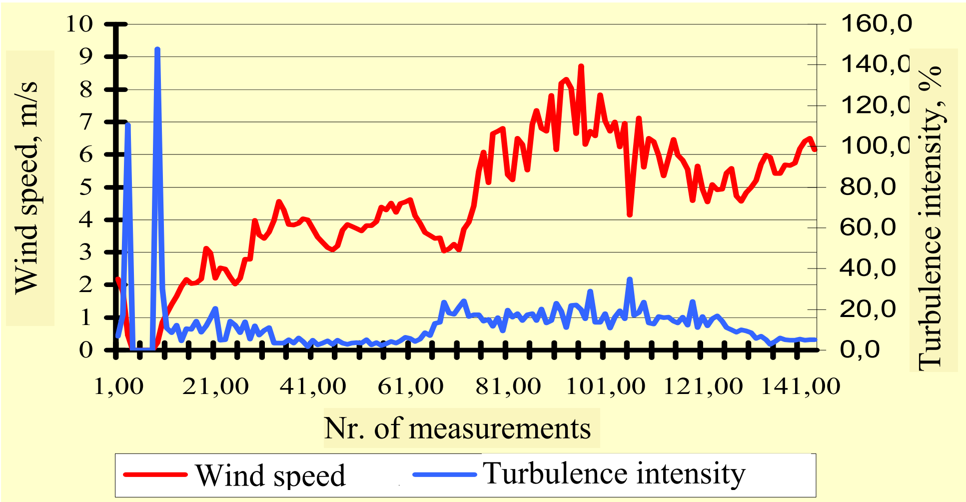


Fig. 4.6. Variation of wind velocity and turbulence intensity: period of observations – 24 h; number of measurements -144.

Figure 4.6 presents the variation of turbulence intensity for a period equal to 24 h. The smaller is the average velocity for a 10 minute period, the bigger is the intensity of turbulence. To draw conclusions about the turbulence it is necessary to have the results of wind velocity measurements for less than 10 minutes for periods of 10 years, at least.

Extreme winds. Wind turbines must be designed so as to withstand the extreme winds or gusts of wind. If the wind velocity is bigger than 25 m/s the wind turbine is broken or taken out from under the wind action.

2.2. Methodology of wind power potential estimation

To calculate the average wind velocity, power density, wind rose and the probability density function of the wind speed, and, further on, to estimate the wind energy potential, two models are currently used: the model developed by the EU countries, known as WAsP (*Wind Atlas Analysis and Application Program*) [8,9], on which basis the European Wind Atlas [10] for 15 EU countries was developed; this model is based on the theory of air currents, and the American model, developed by NASA and U.S. Air Force, based on the theory of climate dynamics [11].

The American model has been recently developed; it has many possibilities, including modelling of wind climatology in the mountainous territory. The MesoMap soft requires a huge capacity of the computer network - 4 Cray C90 supercomputers. For this reason, the soft is not sold, and the *AWS truewind* company offers only services in the field.

High efficiency of the WASP soft, the optimum ratio *price/quality* has induced several countries in the Central and Eastern Europe, including the 10 new EU members, to use it for the assessment of the wind potential to draw their own atlases similar to the European approach.

In the framework of some projects studies on wind climatology statistics were carried out by authors, the Wind Atlases for ten meteorological stations (out of the existing 17) were developed, measurements of the wind characteristics have been performed at a height of 50 m above the ground at three sites located in the south and central regions of Moldova, and the wind energy potential in the south of the country was estimated, as well. The results of the study were published by authors in [12-17]. These studies were based on the methodology accepted in the EU countries and on the WAsP software.

WAsP soft allows two operating modes:

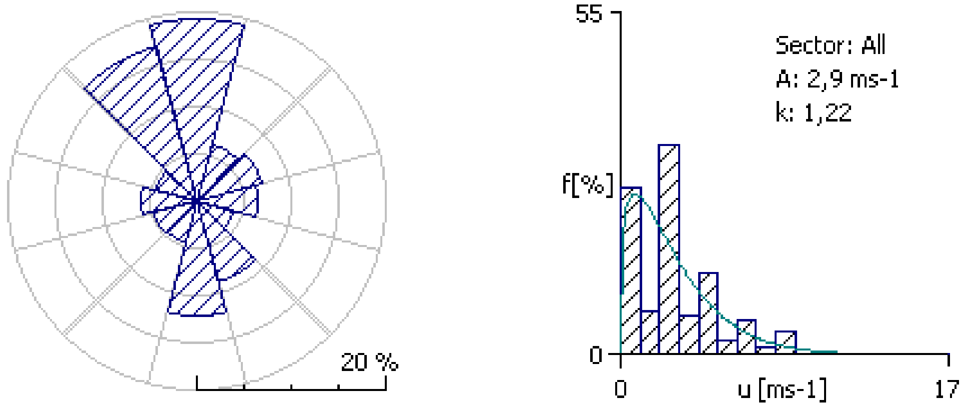
1. Analysis of primary data about the wind in order to obtain the Wind Atlas for each weather station (observation point) separately.
2. Using the Wind Atlas and the power curves of wind turbines in order to assess the wind energy potential at any point in a radius of less than 50 km from the point where measurements were made.

To get the Wind Atlas of the site where the meteorological stations are located, the following initial information is required:

- Primary data on the wind for a period of not less than 10 years;
- Description of the meteorological station site by pointing out the roughness of surroundings and existing obstacles in the immediate vicinity of the measuring device;
- Digital map of the region.

2.3. Statistics of wind climatology and the Wind Atlas

Statistics of wind climatology is presented graphically by interpreting the wind direction (the wind rose) and the distribution of the wind speed probability density function (histogram obtained using the methodology described in p. 2.1) and in tabular form - the rate of the wind velocity for each sector. Fig. 4.7 shows an example of wind climatology statistics at one of the meteorological stations [10].



Wind rose		**Share of wind velocity for each sector, in % Wind velocity, m/s**											**Weibull distribution**	
Sec. [°]	**%**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**A**	**k**
0	19,2	12	5	43	6	17	3	6	1	5	1	1	3,5	1,4
30	6,2	36	11	21	12	9	4	3	1	2	1	0	2,8	1,3
60	7,0	32	6	32	5	14	1	4	0	5	0	1	2,9	1,2
90	6,3	36	6	36	4	9	1	3	1	4	0	0	2,8	1,4
120	4,1	55	7	14	7	7	3	4	2	1	0	0	2,1	1,0
150	8,8	25	5	33	6	17	3	7	2	2	0	0	3,0	1,4
180	12,0	19	6	41	6	14	3	7	1	3	0	0	2,8	1,2
210	4,5	50	16	18	6	4	2	2	1	1	0	0	1,8	1,1
240	4,8	46	11	26	3	7	2	3	0	2	0	0	2,2	1,2
270	5,8	37	8	35	3	9	1	3	0	3	0	1	2,7	1,3
300	4,5	49	11	20	6	7	3	2	1	1	0	0	2,1	1,1
330	16,8	13	4	36	7	18	3	9	2	7	0	1	4,0	1,52
Total		**27**	**7**	**33**	**6**	**13**	**3**	**5**	**1**	**4**	**1**	**0**	**5,3**	**2,9**

Fig. 4.7. Example of wind climatology statistics at one of the meteorological stations.

The distribution of wind speed probability density function, i.e. the histograms are approximated by the Weibull distribution function [10]

$$F(V) = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} \exp\left(-\left(\frac{V}{A}\right)^{k}\right) \tag{4.2}$$

where A and k are Weibull distribution parameters, A is the scale parameter, and k – is the shape parameter.

By applying the Weibull parameters the average annual wind velocities at each meteorological station were estimated

$$\overline{V} = A \cdot G\left(1 + \frac{1}{k}\right), \tag{4.3}$$

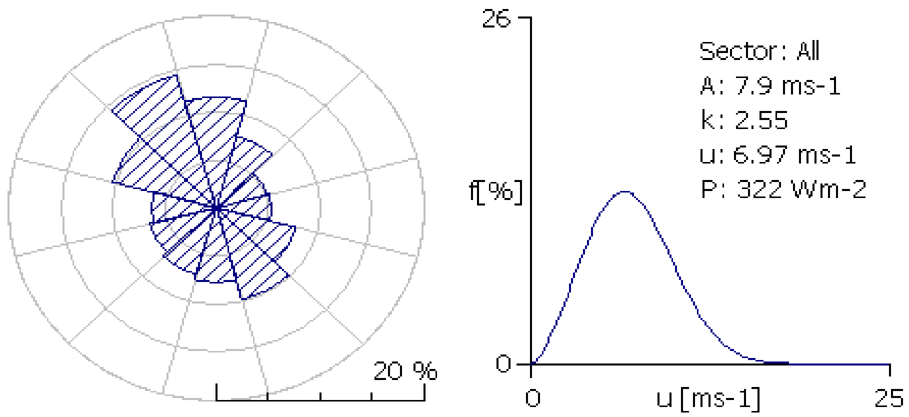
where *G(1+1/k)* is the second Eulerian integral, which values are given in [10].

The Wind Atlas (WA). In the context of the wind energy sector, the concept of the Wind Atlas (Figure 4.8) has a much broader content [7]. The Wind Atlas contains not only maps, graphs, images, which are characteristic for all common atlases, but, first of all, primarily numerical data in tabular form on the wind speed and power density in W/m^2. WA is developed both for presenting data on wind energy resources in a given area (weather station), and in order to provide these data to estimate the wind energy potential in the surrounding region. Its purpose is also to identify places where wind potential is stronger.

To compile the Wind Atlas the following is needed: statistics of wind climatology at meteorological stations, numerical description of the land around the anemometer's site with account of roughness and obstacles and the digital map. The table presents the annual average wind speeds and wind power densities for five predefined heights (10, 25, 50, 100 and 200 m above the ground level) and four roughness classes reported to standard conditions: 0,0; 0,03, 0,1 and 0,4 m. In the upper left side, the wind rose is given, and on the right - the average parameters (for all sectors) A and k of the Weibull distribution and probability density function of the wind speed. Both the wind and Weibull distribution can be obtained for each of the 12 sectors and the average for all sectors.

It should be noted that WA refers to a certain point - the station where measurements were made. Based on these data, we can calculate the same characteristics for any location in the neighbourhood, in the radius of 50 kilometres. It is obvious that for a new site, where the weather data was not recorded, it is necessary to have information about the obstacles, roughness, and relief character. This information is obtained as a result of field investigations, which are processed and adapted to the WASP software requirements.

There is an essential difference between the information contained in the Wind Atlas and the statistics of the wind climatology presented above. The figures in the table mean the average wind speed and wind power density for various heights and different roughness classes. The figures in the first column are the speeds and power densities that would have occurred in the given location if the roughness of the terrain and obstacles would not overshadow the measuring device. In other words, these are data "*cleaned*" out of the negative



Height, m		**Roughness class**			
		R-0	**R-1**	**R-2**	**R-3**
10	m/s W/m^2	7.0 322	4.8 125	4.2 83	3.4 40
25	m/s W/m^2	7.6 414	5.8 201	5.2 147	4.4 88
50	m/s W/m^2	8.2 505	6.7 285	6.1 220	5.3 145
100	m/s W/m^2	8.9 656	8.0 458	7.3 352	6.4 235
200	m/s W/m^2	9.8 920	9.9 909	9.0 678	7.9 438

Fig. 4.8. An example of Wind Atlas for a site

influence of terrain peculiarities. For example, the R-0 roughness class corresponds to a stretch of calm water level. Moving us into another geographical point, for example, in the location of another wind plant, using the WA data calculated for the meteorological station nearby and the data describing the new location, the average wind speed and wind power density for the 5 heights and the 4 standard classes of roughness are calculated.

Methods used to validate the European Wind Atlas (EWA). Measuring the wind characteristics for a minimum of one year period is expensive. In p. 2.3 it was mentioned that 5 of the 17 meteorological stations can be considered as representative and the historical data about the wind can be used to calculate the wind speed and wind direction at a point of interest where no measurements were made. Obviously, the question is: what is the certainty of the calculated results? To answer this question, various validation procedures have been used, taking into account both the methods used to validate EWA and the information available in the Republic of Moldova. EWA validation was performed using the following methods [10,17]:

1. By mutual comparison of the results of measurements and calculations of the average wind speed and Weibull parameters. Mutual comparison procedures include the following: one of meteorological stations is the forecast weather station, e.g. for example the MS1 station in Fig. 4.9. The average speed and Weibull parameters for the forecast station are calculated using the historical data from other stations in the same area - MS2, MS3 and MS4, called forecasting stations. The calculations are repeated four times, pointing in succession as the forecast station another station;

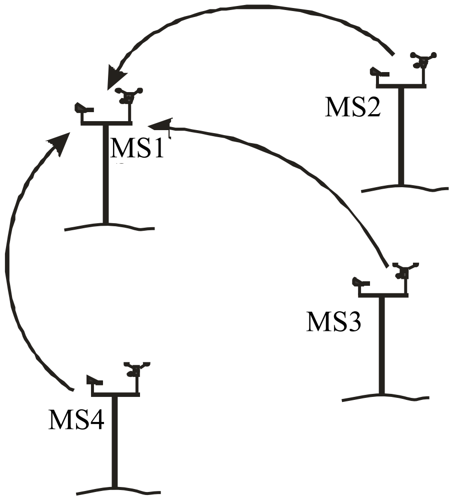


Fig. 4.9. Principle of validation by reciprocal comparison of meteo stations: MS1 – forecast meteorological station; MS2, MS3, MS4 – forecast meteorological stations.

2. The second method consists is the use of the measurements at heights of over 50 m and of wind characteristics for a minimum period of 12 months. In many Western European countries there are data on wind characteristics measured at heights of several tens and even hundreds of meters: the Netherlands – 200 m; Portugal – 100 m; Finland – 220 m; Sweden – 145 m. In this case, the validation of results estimated by calculation is performed as follows (see fig. 4.10): for each tower where measurements were performed on a minimum

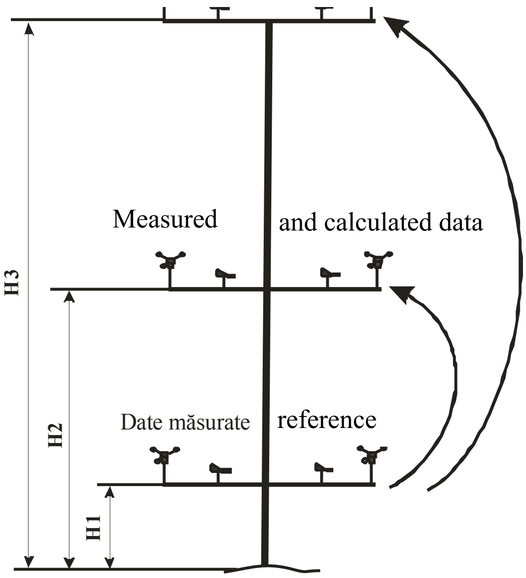


Fig. 4.10. Principle of validation by measuring at various heights.

of 12 months at different heights data are collected corresponding to heights *H1* equal to 10-12 m. These data are used as reference data for calculations. The average speed, Weibull parameters and density of wind power are calculated for heights *H2* and *H3* comprised between 50 and 200 m. The calculated results are compared with those measured.

The principle of validation (Fig. 4.11) consists in comparing the results of calculations of wind characteristics for the same point, using historical data as initial data from weather stations and recent data measurements. The results of validation reported to the site of any wind station are presented in the tables. It can be seen that for a certain location, where no measurements of wind characteristics were made, the wind power density can be predicted with a relative error of 2-12% and the average annual speed - by 1,0 – 7,5%. The error is lower if the reference stations (forecasting) are located in open spaces and are not screened. If the forecasting stations are heavily shielded or are located in hilly areas, then the prediction error is larger.

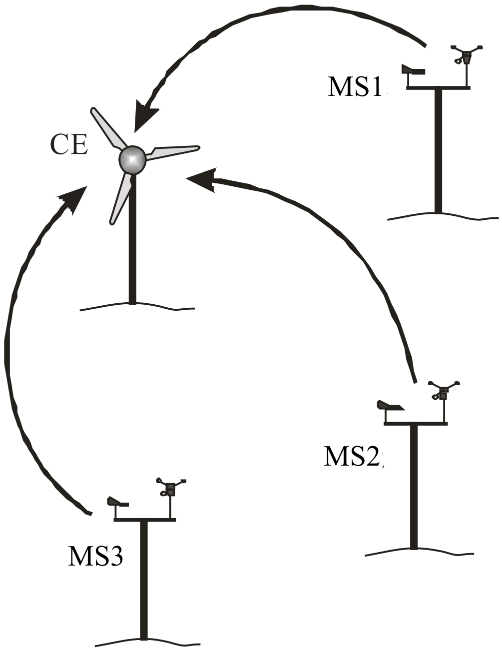


Fig. 4.11. Principle of validation by comparing the results for a wind plant located in a certain place: WP-wind plant; MS1, MS2, MS3 – historical or recent data at meteorological stations

The last validation procedure consists in comparing the annual average speed measured in several locations with the speeds calculated in the same locations at the same height, using the historical data from the nearest meteorological station.

4. Conversion of the air flow kinetic energy into mechanical energy. Betz limit

4.1. Wind energy and power

The energy of a stream of air moving at a linear velocity V is determined by the kinetic energy expression

$$E = m\frac{V^2}{2}\ , \qquad (4.4)$$

where m is the air mass in motion, determined by the air density ρ and the volume that crosses a certain surface S in a time unit

$$m = \rho SV\ . \qquad (4.5)$$

The mass measure unit from expression (4.5) is kg/s and, substituting in (4.4), we will get the air flow power in watts

$$P = \frac{\rho}{2} SV^3\ . \qquad (4.6)$$

The wind specific capacity or wind power density per 1 m^2 is

$$p = 0{,}5\rho V^3\ . \qquad (4.7)$$

At normal atmospheric pressure and 15^0C temperature, the air density is 1,225 kg/m^3. If the height above the sea level varies between 0 and 100 m (modern high-power turbine towers have heights of 60-120 m), the density variation does not exceed 5% and in the first approximation, we consider it constant. Figure 4.12 presents the specific capacity variation of a flow of air in terms of its speed. The rated wind speed for modern high power turbines varies between 12,0 and 15,0 m/s (see the shaded area).

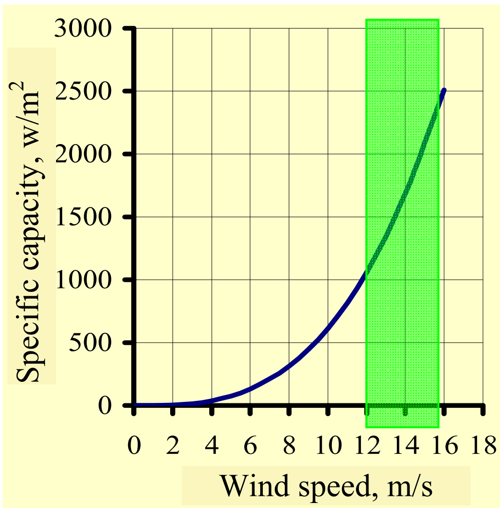


Fig. 4.12. Variation of air flow specific capacity

On the basis of expressions (4.6) and (4.7) the following conclusions can be drawn:

1. Formula (4.5) show the energy potential of a stream of air that crosses the surface *S* or a square meter of surface;

2. Double increase of the turbine rotor diameter will lead to an increase of four times of the air flow power that passes through the rotor surface ;

3. Double increase in the wind speed leads to 8 times increase in the air flow power or specific power;

4. It is very important to know the value of the wind speed and how it varies over time in order to forecast exactly the wind energy potential in a certain locality.

5. It takes considerable effort to get the confidence that the wind station will be located in a locality with the highest wind speeds. In some countries, relatively high towers (more than 60-80 m) are exploited, to take advantage related to speed increase with increasing height.

It is obvious that not all air flow power expressed by the formula (4.6), will be transformed into mechanical energy and then into electricity by the wind turbine. A considerable part of energy will be preserved in the air flow leaving the area adjacent to the turbine; otherwise the last will not work.

4.2. Wind turbine in the air flow

The wind turbine converts the kinetic energy of the air flow that passes through an area swept out by the rotor into mechanical energy, then using the generator - into electricity. The question arises: what happens by placing the turbine rotor in an air flow? It is obvious that the air flow gives up only part of the kinetic energy (see the next paragraph), the remaining energy is consumed so as the air leaves the area of flow - turbine interaction. Figure 4.13 shows an airflow with the initial speed V_0, which crosses the circular area A_0 and interacts with the turbine rotor with the scavenged area A_1. In section A_1, the air flow encounters resistance, the pressure increases, and the speed decreases to V_1. Giving up part of the energy the air flow leaves the turbine with the speed V_2 lower than V_1. As the air mass that passes through sections A_0, A_1 and A_2 remains constant and the speed drops, it follows that $A_2>A_1>A_0$, i.e., there is deflection of the air flow that

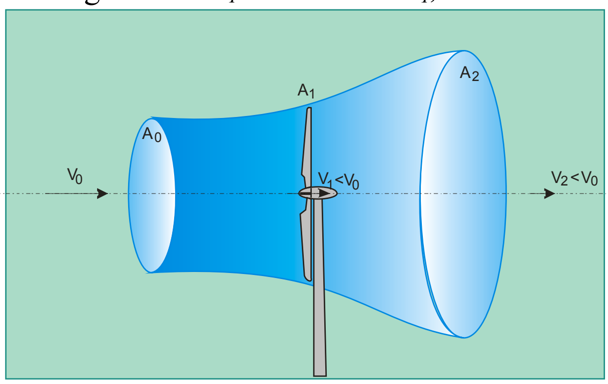


Fig. 4.13. The effect produced by the wind turbine on the air flow

passes through the turbine rotor, forming a funnel. The airflow formed immediately after the propeller is called the propeller slipstream, in which the static pressure is lower than in the free zone of the atmosphere. The static pressure is repressuring at longer distances from the propeller.

4.3. Betz limit

In 1919 the German physicist Albert Betz formulated the law that answers the question: what part of the kinetic energy of the air flow can be converted into mechanical energy? Betz analysed a turbine with an ideal rotor: it is assumed that the rotor presents a disk with an infinite number of thin blades, energy losses are neglected, the flow of air runs through imaginary sections without turbulence in Figure 4.13. Velocity V_0 is the speed of airflow till the rotor, V_2 is the speed of air flow leaving the rotor area, V_1 is the flow velocity in the A_1 section of the rotor. In accordance with the Newton's second law the variation of motion quantity is equal to the force acting on the body:

$$F = \frac{d(mV)}{dt} = m\frac{dV}{dt}. \qquad (4.8)$$

The variation of the air flow velocity for the above model during one second (*dt=1 s*) will be, $dV = V_0 - V_2$, so

$$F = m \cdot (V_0 - V_2). \qquad (4.9)$$

We introduce the concept of air flow braking factor in the turbine $e = V_1 / V_0$ and, assuming that the wind speed varies linearly, determine the air flow speed of the A_1 area of turbine:

$$V_1 = \frac{V_0 + V_2}{2}, \longrightarrow V_2 = 2 \cdot V_0 \cdot e - V_0. \qquad (4.10)$$

According to (4.5) the air mass crosses area A_1 in a second:

$$m = \rho \cdot A_1 \cdot V_1 = \rho \cdot A_1 \cdot V_0 \cdot e. \qquad (4.11)$$

Let substitute in (4.9) velocity V_2 and mass m according to (4.10) and (4.11):

$$F = 2 \cdot \rho \cdot A_1 \cdot V_0^{\,2} \cdot e(1-e). \qquad (4.12)$$

Power developed by turbine is the product of force and velocity:

$$P = F \cdot V_1 = 2 \cdot \rho \cdot A_1 \cdot V_0^{\,3} \cdot e^2(1-e). \qquad (4.13)$$

According to (4.6), the air flow output with velocity V_0

$$P_0 = \frac{1}{2}\rho \cdot A_1 \cdot V_0^{\ 3} \text{ or } 2P_0 = \rho \cdot A_1 \cdot V_0^{\ 3}. \tag{4.14}$$

Substituting in (4.13) we obtain

$$P = 4 \cdot P_0 \cdot e^2 \ (1-e) = P_0 \cdot C_p, \tag{4.15}$$

where

$$C_p = 4 \cdot e^2 (1-e) \tag{4.16}$$

is called the power factor (efficiency factor) of Betz limit. Differentiating the expression (4.15) with respect to e , we determine its value for which power P will be the maximum. The result is *e=2/3, Cp=16/27=0,593.*

We can draw the following conclusion: the air flow will give up to an ideal turbine not more than 59,3% of its original power P_0 and this will be achieved when the braking factor $e = 2/3$ and air flow velocity after the turbine will be V_2 = 1/3 V_0. In fact, the best three-bladed wind turbines have the Betz coefficient equal to 0,45 – 0,50.

4.4. Number of blades and rotor diameter effect

Betz limit states that an ideal wind turbine can extract from the wind a power not exceeding 59,3%, but the analysis made above does not indicate the operating system of the turbine or the construction that the rotor must have in order that the maximum power factor is achieved. Next, we will undertake a qualitative analysis of the turbine operating mode and of the effect of the number of blades or the solidity factor on the value of power factor. Also, the dependence of the rated power on the commercialized turbine rotor diameter is analysed.

The efficiency of air flow energy conversion into mechanical energy will be lower than the optimum value if:

1. The turbine rotor has a bigger number of blades (the solidity factor is big) or the rotor turns with a very high frequency and each blade moves in an air flow distorted (turbulent) by the front blade.

2. The turbine rotor has a small number of blades (the solidity factor is small) or the rotor turns with a very slow frequency and the air flow crosses rotor’s surface without interacting with it.

In order to achieve maximum energy conversion efficiency it is necessary to correlate the rotor’s speed of rotation with the wind speed. To characterize the wind turbines with different aerodynamic parameters, the dimensionless parameter is applied, called the tip *speed ratio* λ. The speed ratio links in a single formula three important variables of the turbine: the rotational speed ω, the rotor radius (or diameter) R and the wind speed V, and is defined as the ratio between *linear* turbine *blade* tip *speed* U to the wind *speed*

$$\lambda = \frac{U}{V} = \frac{\omega R}{V} \tag{4.17}$$

A turbine of certain design will operate in a large range of variations of the tip *speed ratio* λ, but will have maximum efficiency C_p only for an optimal value of the speed, or, if linear velocity U is equal to the wind speed multiplied to the optimal value of the tip *speed ratio*.

Figure 4.14 shows C_p–λ characteristics taken from [25] for turbines with different number of blades. Analysis of these characteristics allows drawing the following conclusions:

1. The smaller the number of blades the greater the optimum *tip speed ratio* for which the power factor or energy conversion efficiency is maximized.

2. Two equal power turbines, but with a different number of blades are distinguished by the fact that the multi-blade turbine will develop a higher moment and will have lower rotation speed and vice versa - the turbine with few blades will develop a small moment but will have a higher rotational speed.

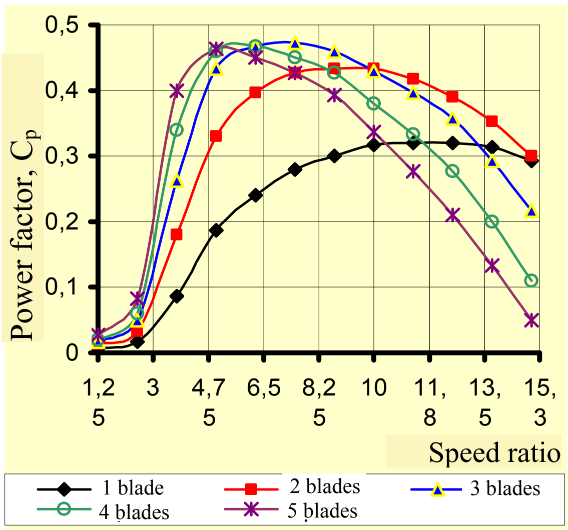


Fig. 4.14. Aerodynamic characteristics of different turbines.

3. Three-bladed turbine has the biggest factor of efficiency. The differences between the factors of maximum efficiency of 2-5 blade turbines are not significant. Advantages of 1 or 2 blade turbines consist in the possibility of operation in a wider range of *tip speed ratio* variation, in which the efficiency factor is maximum or close to maximum.

4. The maximum efficiency factor (Betz) of the turbine with 12 – 18 blades is smaller than that of the turbine with 3 blades and does not exceed 0,35.

Dependence of the turbine output power on the rotor diameter. Low power turbines have towers with relatively bigger heights than the high power turbines. This is explained by the necessity to exclude the negative influence of the ground surface layer and obstacles on the wind speed. For rotor diameters between 5 and 10 m the ratio of the tower height and rotor diameter is equal to 6-2. Starting with diameters equal to or bigger than 30 m, this ratio varies around the digit 1. Obviously, the specific costs of smaller turbines will be higher.

Mechanical power generated by the turbine is proportional to the rotor diameter square. The wind speed will increase simultaneously with the increase of diameter and height of the tower. Usually, the increase of the wind speed is considered proportional to the heights ratio of the exponent 1/7 [3,5]. Thus the turbine power is proportional to the rotor diameter of the exponent (2+3·1/7) = 2,42. For turbines currently marketed a good approximation is given by the expression [3]:

$$P = 0{,}06 \cdot D^{2{,}42}, \qquad (4.18)$$

where D is the rotor diameter, in m; P is rotor power, in kW.

Fig. 4.15 and 4.16 show qualitative and quantitative evolutions of modern turbines capacities. The solid line (fig. 4.16) corresponds to the analytical expression (4.18).

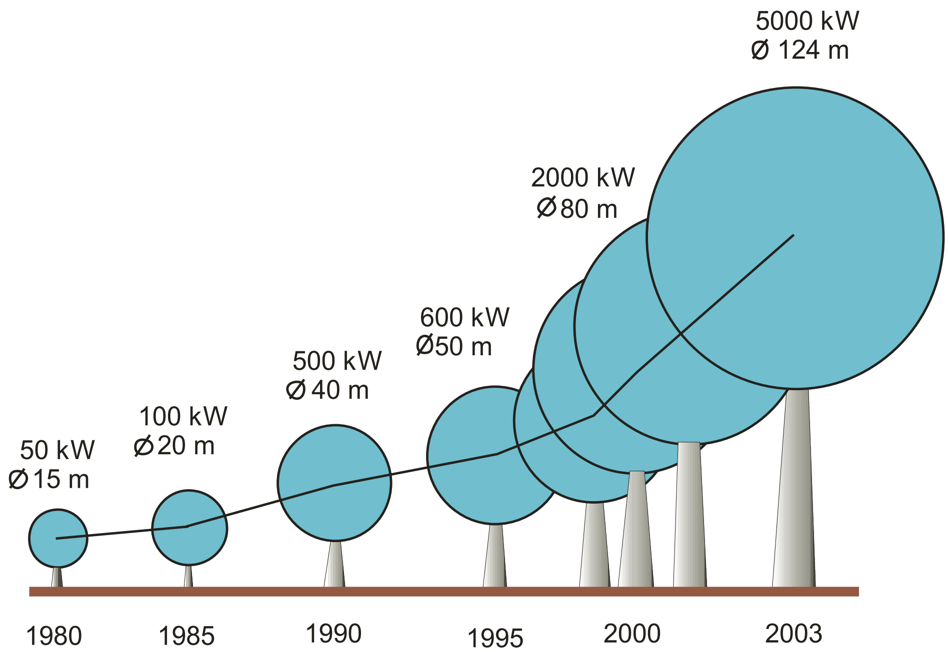


Fig. 4.15. Rotor diameter and capacity increase for sold turbines.

There is a tendency worldwide to increase the rotor diameter, even when the rated output remains the same. For example, the average diameter of the rotor of 1,5 MW turbines designed before 1997 was equal to 65,0 m in diameter; in 2000 the diameter reached 69,1 meters and 73,6 m in 2003. Increase in the rotor diameter leads to an increase of the extracted energy from the wind. If rated output remains the same the wind calculated speed can be decreased. Thus, the area of wind turbines use widens, including the new areas with average and small wind energy potential. This trend is also reflected by the empirical expression (4.20): for the turbines designed after 2003 the rated output can be calculated with the expression

$$P = 0{,}000195D^{2{,}156}. \qquad (4.19)$$

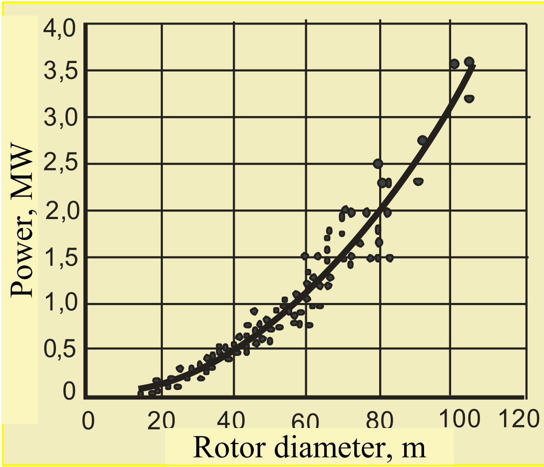


Fig. 4.16. Rated power of commercial turbines depending on rotor diameter

Linear velocity of the blade tip is the product of the rotational speed and rotor radius. For turbines with rated power of 0,6 to 3,6 MW the range of linear velocity varies between 43,0 and 90 m/s (155-325 km/h). Such linear velocities require strict design of the aerodynamic profile, ensurance of surface good quality and excellent dynamic balancing of the rotor. All these measures lead to considerable reduction of noise and allow immediate placement of modern turbines near the villages and towns.

5. Evolution of wind technology development

5.1. Commencement of commercial technologies

The period before 1970. The largest wind turbine for electricity production was built in the area of Grandpa Knob, Vermont, USA [3,5]. The 1250 kW turbines and 53 m rotor diameter was the outcome of collaboration between engineers Smith Putnam, von Karman and den Hartog. This was the first turbine which power was more than one megawatt and served as a platform for experimental studies of the fatigue effects of materials for blades and tower, EECS dynamics and verification of the data imposed by the project. However, the landmark year for launching the modern wind technology is considered 1957, when Johannes Juul, Danish engineer, designed the first wind 200 kW turbine, manufactured in northern Denmark, Gedser area (Fig. 4.17) [19]. He was the first who took the theory of airplane wing and transposed it in the construction of wind turbines. The turbine was installed on a 25 m tower and had three rotor blades. It was equipped with self-control system and self-stopping at the wind speed allowable limit exceeding, with electromechanical orientation drive and induction generator. It worked until 1967 with an average power factor of about 20%. Subsequently, the turbine is known as "*the Gedser turbine*" or the "*Danish concept*". Currently over 75% of the wind power (medium and large) turbines are based on the "*Danish concept*" [5], characterized by three thin-bladed rotor with aerodynamic profile oriented towards the wind and rotates at a relatively high speed - tens or hundreds of revolutions per minute depending on the diameter of the propeller. The innovative concept and characteristics of this model were soon recognized worldwide; Denmark became the main exporter of wind turbines and has over 33% of the global market.

Fig. 4.17. The first turbine manufactured on the basis of the „*Danish concept*" by J. Juul in Gedser, Denmark [19].

The period 1970-1990. The results of experiments with different materials for blades have led to the abandonment of steel as a material too hard, as well as the aluminium that did not cope with dynamic stresses. Gougeon Brothers (USA) proposed wood and epoxide resin based material used in the construction of small and medium power turbines.

Due to a successful combination of federal and state laws concerning facilities granted to the wind energy sector, the first wind boom started in California: 1700 MW wind power were installed (5,7 times more than the installed capacity of Thermo-Electrical Power Plants in the Republic of Moldova) in the period 1980 – 1995. The Californian boom has had a negative side - technical performances of the wind turbines were poor and have been placed irrationally which fact generated distrust in the wind energy. However, the U.S. market and facilities have enabled European producers to export and test more types of turbines and develop the foundation of modern technology.

Period between 1990 - present. The wind energy development in California was not sustainable. After cancellation of some facilities a period of stagnation has started. Instead, the European markets have developed rapidly. In Germany, in the early ‘90s, the rate of wind power growth reaches 200 MW/year. New producers have emerged in Germany, Spain, and USA. New technological concepts have been developed: the outstanding innovative scheme of the wind generator with direct coupling (*direct drive generator*), variable rotational speed turbine, flow control systems for the power supplied to the grid, composite materials for blades, etc.

5.2. Wind turbine design

Wind turbines can be classified into four major groups, depending on the power developed at the wind rated speed, which is between 11 and 15 m/s. Micro turbines cover powers between 0,05 and 3,0 kW. Low-power wind turbines range from 3 to 30 kW and medium power turbines range between 30-1000 kW. Both micro turbines and low power turbines are designed to operate in autonomous mode; these turbines supply electricity to territorially dispersed consumers that are not connected to the public power grid. To this end, the turbines are fitted with electrical energy batteries and power conditioning devices - controllers and frequency converters. The fourth group includes turbines with greater power – over 1000 kW, called high-power turbines or multi-megawatt turbines. The current trend is power increase per unit, the absolute majority of the turbines operate in parallel with public electricity network, and priority is given to turbines with bigger power than 1 MW.

Over the years hundreds of wind turbine construction schemes have been proposed and patented, but several dozen have been tested only, of which only a few have penetrated the wind turbines market. Figure 4.18 presents the most significant structural schemes of the wind turbines.

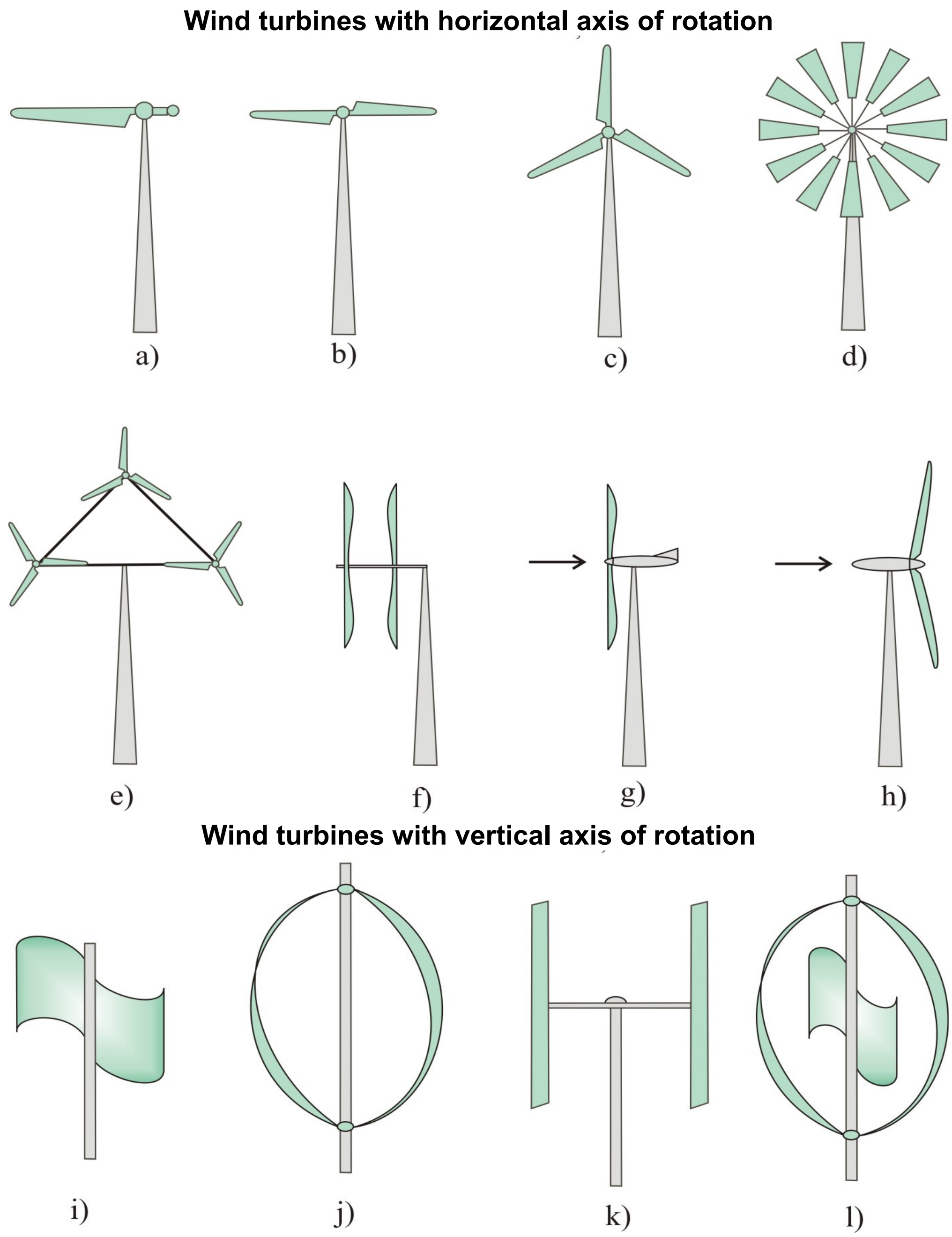


Fig. 4.18. Wind turbine design: a,b,c – with 1-, 2- or 3-blades; d – multi-blade; e – with more rotors; f – with two rotors turning in opposite directions; g – with rotor at tower front and weathercock (up–wind); h – with rotor at tower back with self-control (down – wind); i – Savonius; j – Darrieus; k – Evence; l – combined Darrieus – Savonius.

Wind turbines: with horizontal or vertical axis of rotation? The answer to the question is in favour of the turbines with horizontal axis of rotation (Figure 4.18 a-h). The absolute majority of the sold turbines are horizontal axis. The turbine axis of rotation coincides with the direction of the wind turbine and is parallel to the ground surface. In turbines with vertical axis the wind direction is perpendicular to the axis of rotation, respectively, perpendicular to the ground surface (Figure 4.18 i-l). Although vertical axis turbines have lost the competition, engineers come back again and again to this design scheme, the main reason being the following two indisputable advantages:

- The generator, the multiplier and other functional components can be placed on the ground surface; the gondola and massive tower are not required;
- The turbine does not require a special device to track wind direction.

Unfortunately, the disadvantages of these turbines prevail compared to the advantages:

1. Wind speed in the adjacent to the surface layer is small. Thus, we save on tower construction, but lose the power developed by the turbine.

2. Wind energy conversion factor into mechanical energy is lower.

3. Some types of turbines, such as the Darrieus or Evence turbines do not provide starting. An auxiliary motor is required to start the turbine or a small turbine of Savonius type.

4. High power turbines need support cables, which considerably increase the occupied land area.

5. Replacing the main thrust bearing requires complete disassembly of the turbine.

Below we briefly describe the construction schemes shown in Figure 4.18. A key feature of the horizontal axis turbine is the number of blades. There may be one, two, three or more blades (see figure 4.18, a-d). If the turbine has more blades, the solid area of the rotor swept area is bigger. The theory of wind turbines states that the number of blades is taken into account with the solidity factor that shows the relationship between all blades' area and the area swept by the rotor. It is obvious that 1- or 3-blades turbine have a lower solidity factor than the turbines with 12 or 18 blades. The effect of the number of blades on the turbine performance is described in paragraph 4.4. The bigger the solidity factor (multi-bladed rotor), the smaller is the rotational speed of the turbine, and the developed moment is bigger too, and inversely. For this reason, the turbines with fewer blades are used to generate electricity, and the multi-blade turbines are applied for pumping water, driving saws, crushers, grinding rollers, etc. In other words, multi-blade turbines are used in machines that require low speed of rotation and big moments on start-up.

Other constructive schemes of horizontal axis turbines are shown in figure 4.18 e–h: e – multi-blade turbine; f – turbine with 2 rotors, that turn in opposite directions; g – with rotor at tower front (*up – wind*) and weathercock for orientation; with rotor at tower back with self-control (*down - wind*). Fig. 4.19 shows a modern horizontal axis turbine, type V90– 2, 2 MW power, rotor diameter is 90 m [19].

Vertical axis turbines are shown in Figure 4.18 i–l: Savonius turbine with S-type rotor (i), Darrieus turbine with rotor – ellipse (j), Evence turbine with H-type rotor (k), Turbine with combined rotor – Darrieus – Savonius (l). Examples of vertical axis turbines are presented in figures 4.20, 4.21.

Fig. 4.19. Modern horizontal

Figura 4.20. Darrieus turbine [19].

Fig. 4.21. Turbine H, 420 kW, Crimean peninsula, Ucraine.

5.3. Principles of control of wind turbine power output to the grid

The wind turbine will provide rated output in the network, if the wind speed is equal to the calculation speed, usually 11 to 15 m/s. For higher wind speeds it is necessary to limit the mechanical power, respectively, the overstressing of the rotor blades, multiplier, generator, tower etc. Thus, there is need to control the power turbine. The most common control methods are as follows [7,8]:

- *passive stall control*;
- *active pitch control*;
- *active stall control*;
- *yaw control.*

Power control using the passive stall control method. It is the simplest method and can be used for turbines with constant rotation speed, i.e. the speed of rotation does not depend on the wind speed or varies slightly (1-2%). Constant rotation speed of the turbine can be obtained in EECS equipped with asynchronous or synchronous generators connected directly to the public power grid (figure 4.22 b). Rotor blades are fixed rigidly and have aerodynamic shape, providing a laminar character to the air flow for wind speeds between the start V_p and calculated V_c velocities (Fig. 4.22, c). For wind velocities bigger than V_c (Fig. 4.22, a), the air flow motion above the blade becomes turbulent, the lifting force decreases and the resistance force increases, and respectively, the mechanical power decreases.

The typical form of power characteristics *P =F(V)* for a turbine with stall control is shown in Figure 4.28 d. In the velocity zone $V_p < V \le V_c$, power output to the network is proportional to the cube of the wind velocity. At the calculated velocity, the turbine generates rated output, and if the wind velocity continues to increase, aerodynamic braking intensifies and the increase power output is limited. In most cases, for velocities equal to or greater than 25 m/s, the turbine is disconnected and broken by the mechanical brake from the equipment. The main advantage of this control method is to achieve simplicity, the disadvantages consist in the fact that this method requires a rigorous calculation of the aerodynamic blade profile; the generator must withstand overstresses of 20-30%, for high wind velocities (turbulent

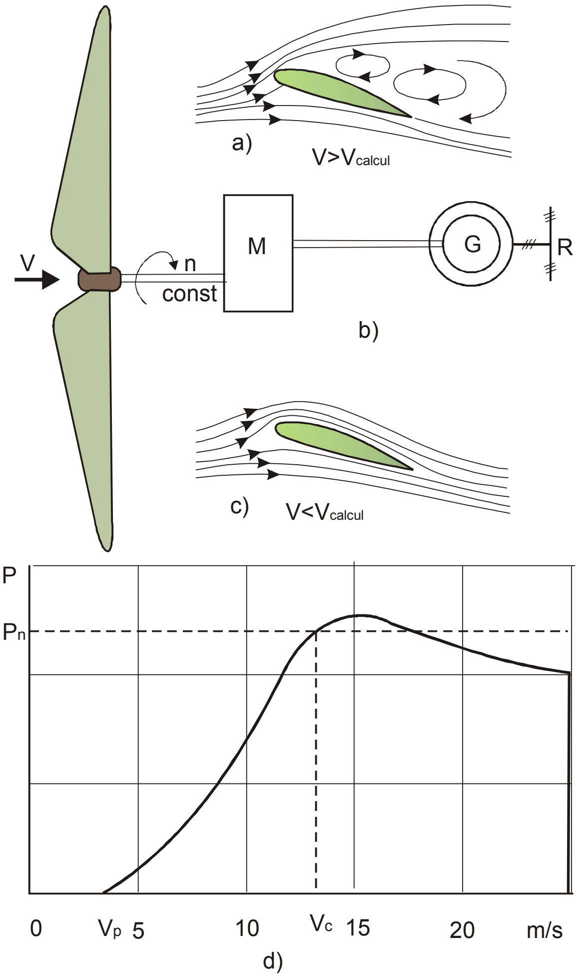


Fig. 4.22. Principle of control of rated output to the grid using the stall control method

movement intensifies) the generated power in the network becomes less than the rated output.

Power control using the active pitch control method. Control of power output is achieved by controlling the adjustment angle α (Figure 4.23 a). For this purpose the blade is rotated by a special device around the longitudinal axis. Turbine rotational speed can be variable. To maintain constant frequency, the synchronous generator is connected to the network using frequency converter (Fig. 4.23, b). For small adjustment angles, ranging from 0 to 13 - 15 degrees, the aerodynamic *lift force* increases linearly with increasing the angles of adjustment:

$$F_L = \frac{\rho}{2} C_L A_P V^2, \quad (4.20)$$

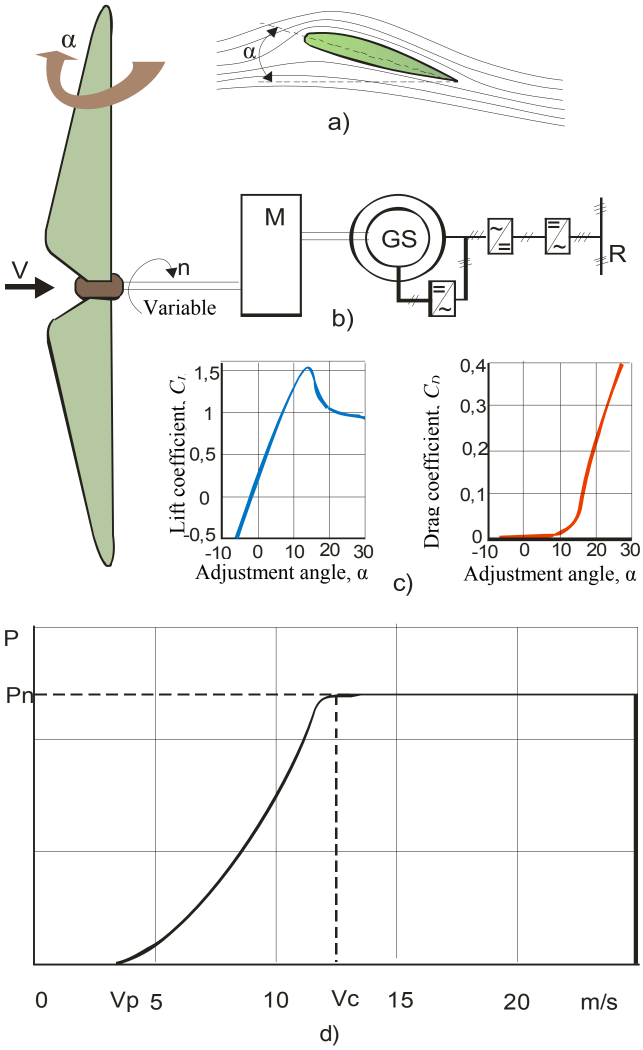


Fig. 4.23. Principle of control of power output to the grid by using active pitch control method.

where C_L is the lift coefficient; A_P is the blade area (so-called master-sectional area or area of the blade projection to the surface perpendicular on the wind direction); V is the wind velocity; ρ – air density.

Also, the *drag force FD* appears, which direction coincides with the wind direction:

$$F_D = \frac{\rho}{2} C_D A_P V^2, \quad (4.21)$$

where C_D is the drag coefficient.

Typical variation of coefficients C_L and C_D, and respectively, of the forces F_L *and* F_D for aerodynamic blade with NACA632XX profile is shown in Figure 4.23 c. For wind velocities bigger than the nominal velocity the mechanical power is kept constant by increasing the angle of adjustment α, coefficient C_L decreases sharply and C_D increases, power output remains constant (see figure 4.23 d). The main advantage of the active pitch control method consists in reducing the mechanical stress on the blades, rotor and tower; wind energy conversion efficiency increases with 2-4% at lower velocities than the rated one. Disadvantages - the complexity of implementation, the need for a system of rapid adjustment of the entering angle.

Active stall control method. It is a combination of the two methods – passive stall control and active pitch control. At wind speeds lower than the rated velocity, the angle of adjustment is controlled to obtain greater efficiency of the wind energy conversion into mechanical energy. For wind velocities higher than the nominal velocity, the angle of adjustment is controlled in the opposite direction to the original one for the pitch control, usually the setting range is $0<\alpha<-5^0$. From Figure 4.23, c it shows that for these angles of adjustment the lift coefficient decreases, and respectively, the lifting force is reduced, so the mechanical power is constant.

Power limit by removing the turbine rotor from the wind direction. This method is recommended only for power turbines less than 30 kW. At high wind velocities the turbine rotor is removed from the direction of wind either by turning it around the tower axis (*yaw control*), or around the axis perpendicular to the tower axis (*tilt control*). In both cases, passive mechanical systems are applied that react to wind velocities higher than the nominal velocity.

The analysis of small power turbines projects depending on the power control method is shown in Figure 4.24. Figure 4.25 shows turbines with power more than 1 MW [3, 5]. In 57% of the implemented projects the method of turbine rotor removal from the wind direction is applied, and about 17% of turbines are not equipped with power control systems. The turbine rotor without power control is calculated to withstand extreme winds in the area. In high-power turbines clear trend is found of increasingly wide use of control by adjusting the entering angle or by pitch control (fig. 4.24).

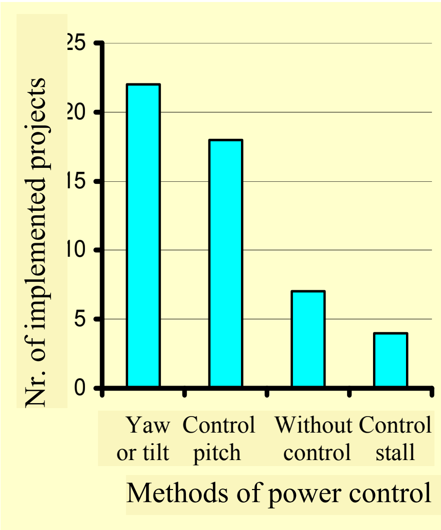


Fig. 4.24. Methods of power control used for small-power turbines.

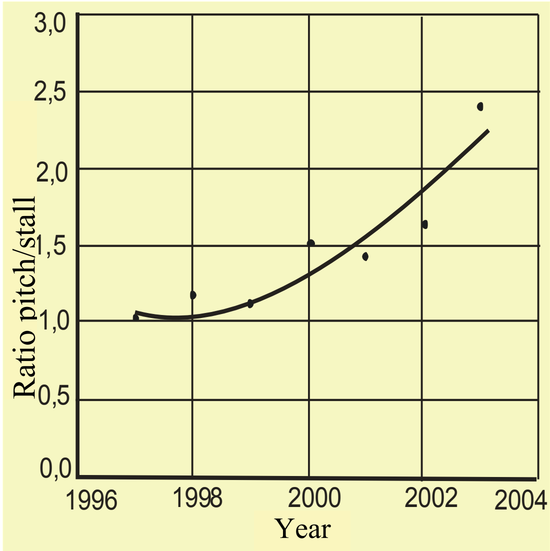


Fig. 4.25. Ratio of control methods for power used in turbines bigger than 1000 kW.

5.4. Constructive schemes for generator operating

The first marketed wind turbine, built by J. Juul, in the area of Gedser, that generated the "*Danish concept*" (see p. 5.1) was equipped with multiplier and asynchronous generator. This diagram (Fig. 4.26, a) prevails today in most turbines with rated power greater than 100 kW. To reduce weight and increase efficiency, asynchronous generator must be designed for rotational speed as big as possible - 3000 min^{-1} at a frequency of 50 Hz and 3600 min^{-1} at a frequency of 60 Hz. However, the 600 kW turbine speed of rotation is about 30 $min^{-1}$and that of the turbines with power bigger than 1000 kW is even smaller. An optimum mass of the multiplier - generator train is obtained for generator rotation speeds of (1000–1500) min^{-1}. In this case the multiplier gear ratio should be about 1:50. The multiplier - asynchronous generator design diagram is not universal and can not be recommended for all wind turbines. The solutions are different depending on the turbine power and area of use.

Micro turbines, rated power equal to or less than 3 kW. The rated speed of rotation of micro turbines is relatively high (200-500 min^{-1}) and used in autonomous regime. Over 95% of turbines are equipped with low speed synchronous generators with permanent magnets (PMSG) and coupled directly with the rotor (Fig. 4.26 b). At low speeds of rotation, the technical performance of synchronous generators decreases essentially and in isolated electrical systems requires special excitation equipment and voltage stabilization. The reference literature has not identified any examples of wind micro turbines equipped with asynchronous generator operating autonomously or supplying a remote power network.

Small-power turbines – (3 – 30 kW). Absolutely all turbines with rated power up to 10 kW are equipped with PMSG coupled directly to the wind turbine. In the 10-30 kW power range there are some exceptions: the wind turbine produced by "*Atlantic Orient Corporation*" (USA) with nominal power of 20 kW is equipped with variable reluctance generator [3].

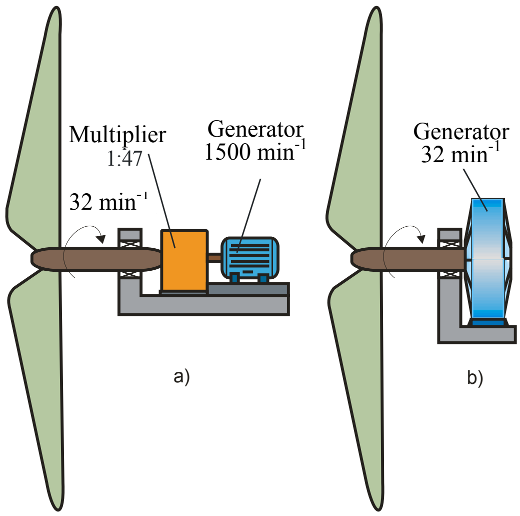


Fig. 4.26. Wind turbine with multiplier (a) and direct coupling (b).

Medium-power turbines – (30 – 1000 kW) and multi – megawatt turbines. This situation is uncertain. The multiplier-generator diagram prevails on the market; the generators can be asynchronous or synchronous with electromagnetic excitation (EMSG), or with permanent magnets. After the '90s of the last century several prototypes of wind turbines with direct coupling were brought to the market, following several objectives:

- reducing the operating and maintenance costs;
- increasing the wind energy conversion efficiency, including areas with moderate winds;
- decreasing the start speed (start) of the turbine, thus increasing the range of lucrative wind speeds;
- reducing the length and weight of the gondola;
- reducing vibration and noise;
- increasing the availability and reliability of wind turbine.

WinWind Finnish Company launched a 1100 kW power wind turbine on the market: the rotor diameter is 56 m, which is a hybrid, a compromise between the diagram with the multiplier and the diagram with direct coupling. The so-called "*Multibrid*" concept [5], which is put at the basis of the new turbines, consists in the use of one-step planetary multiplier with gear transmission ratio of 1:5,7 and PMSG rotation speed between 40 and 146 min^{-1}.

Weight of the multiplier - PMSG train has remained the same as for traditional turbines, but the gondola is a more simple and compact construction.

5.5. Blades manufacturing materials

The ideal material for blades should combine the following structural properties: hardness- weight specific optimal ratio; longevity and flexibility to fatigue; low cost and easy process to get the desired aerodynamic shape. After multiple experiences at the early stage of wind technology development, based on the use of steel, aluminium, etc., nowadays global manufacturing technology for turbine blades is entirely based on the following composite materials:

1. GRP – *Glass Reinforced Plastic*, producers: LM Glasfiber Denmark; Aerpac, Rotorline, Polymarin, The Netherlands.

2. Wood plus epoxide resin, producer: Taywood Aerolaminates (TAL), USA.

3. CFRP – *Carbon Fibre Reinforced Plastic*, producer: ATV Enterprise, France.

Share of the most common materials for blades and the main actors on the world market are shown in Figure 4.27. The trend of decreasing the rotor mass, and increasing the blade elasticity require manufacturers to return to the so-called "*boat building*" technology. Known for decades, this technology is used in large scale construction of different crafts, motorboats, boats, etc. The material is based on polyester resin and contains less glass fibre.

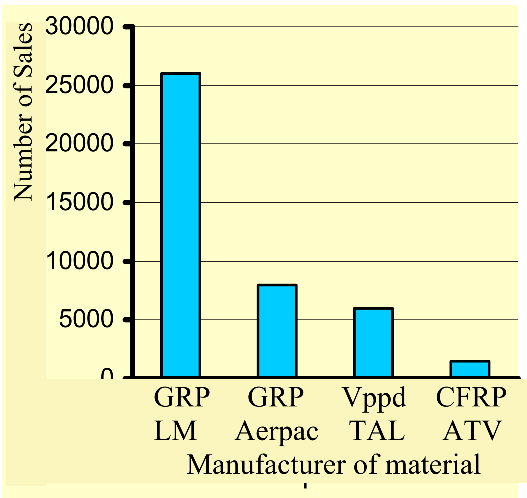


Fig. 4.27. Materials for blades and main producers on the world market.

6. Large wind turbines and farms

6.1. Large wind turbines: trends and objectives

Although the first 1000 kW wind turbines prototypes have been tested long before the 80's of the last century, none of them have been sold. Even operated for short periods of time (Table 4.10) they served as experimental research platforms to gain new knowledge and create the technology for the next step made in the late XX–early XXI century.

Table 4.2. Performance of the first wind turbines prototypes with power over 1.0 MW [23].

Turbine type, country	Rated output, MW	Rotor diameter, m	Operating hours	Generated power, GWh	Years of production
Smith-Putnam, USA	1,25	53	695	0,2	1941– 1945
Mod-1, USA	2,0	60	-	-	1979 – 1983
Mod-2, USA	2,5	91	8658	15,0	1982 – 1988
Growian, Denmark	3,0	100	420	-	1981 – 1987
WEG LS-1, Great Britain	3,0	60	8441	6,0	1987 – 1992
Mod-5B, USA	3,2	98	20561	27,0	1987 – 1992
Ecole, Canada	3,6	64	19000	12,0	1987 – 1993
WTS-4, USA	4,0	78	7200	16,0	1982 – 1994

The *„Danish concept"* for wind energy conversion technology has dominated the world market about 25 years. Although different projects were carried out, they all had the following common characteristics: three blades, constant rotor rotation speed, aerodynamic braking (stall) for power control, asynchronous generator. On world market, turbines of up to 200 kW were mainly sold, rotor blades were made of PFS or wood plus or epoxide resin. And in the late twentieth century an increase in power per unit took place (without changing the "*Danish concept*") - 250, 400, 600 and 750 kW.

Since the year 2000, 1 MW power turbines are emphasized. Rotor diameter reaches 100 m and more. Although the constructive ideology retains some features of the "*Danish concept*" in the newly completed projects the following prevail: rotor variable speed, power control through changing the adjustment angle, more widespread direct coupling, and more frequent use of carbon fibre based material. As a result, the efficiency of converting wind energy into mechanical energy increased, the quality of the electricity network supply improved, noise and vibration were reduced, and multiplier-related problems were excluded. The wind turbine market has become more attractive, sales increased and specific costs decreased. To compare the two technologies, Figures 4.28 and 4.29 show the composition of gondolas of two modern turbines: Z72, Zephyros, The Netherlands [24], rated power - 2000 kW, rotor diameter - 72 m, starting wind speed - 3 m/s, rated speed - 15 m/s, permanent magnet synchronous generator, direct coupling, variable speed, pitch control, gondola weight - 61 t; and V80, Vestas, Denmark [19], rated power - 2000 kW, rotor diameter - 80 m, starting wind speed - 4 m/s, nominal speed - 15 m/s, dual

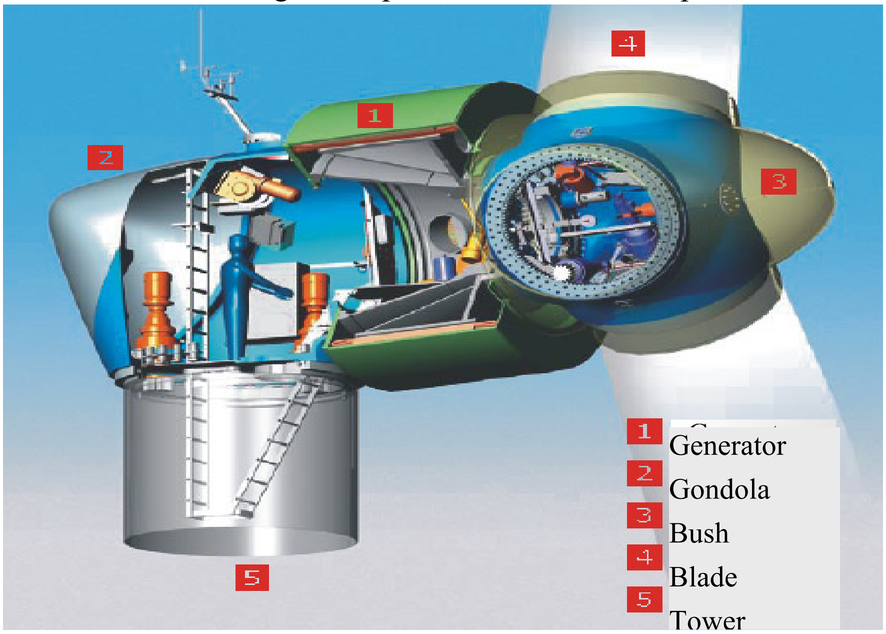
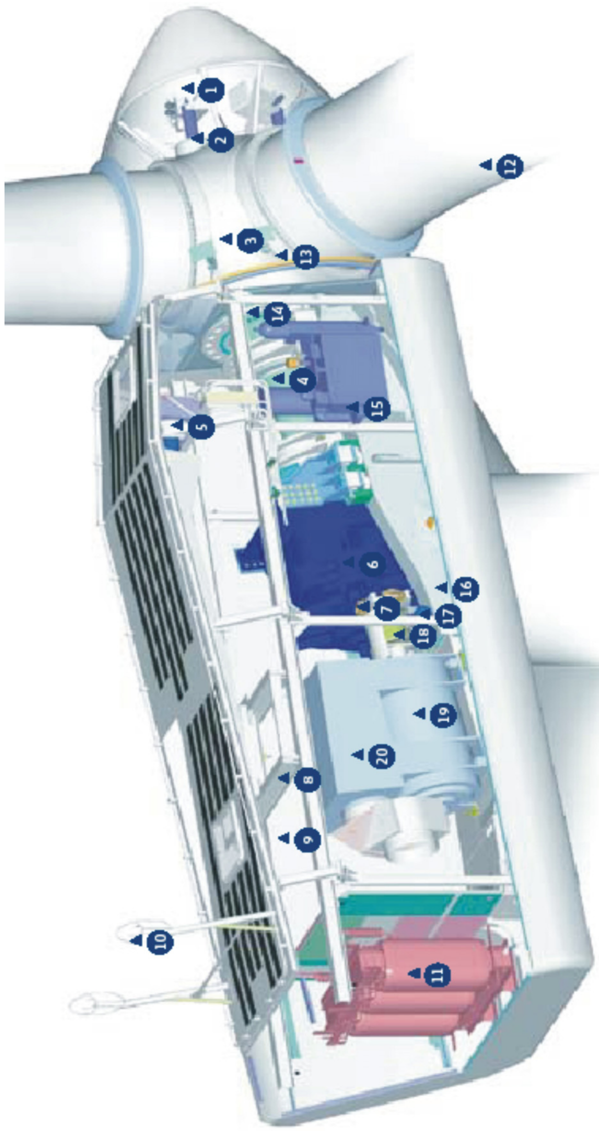


Fig. 4.28. Z72 turbine with direct coupling and permanent magnet synchronous generator.

feed asynchronous generator with multiplier 1:60, variable speed, pitch control, gondola weight - 67 t. In the first variant, the gondola is much more robust and lighter by 6 tons, the number of components and the length of rotor-generator train are significantly decreased.

The main objectives of wind technologies development can be formulated as follows:

1. widespread use of intelligent monitoring and control of mechanical loads and vibrations;



1- Butucul controlerului; 2 - Cilindrul sistemului de reglare a unghiului de atac; 3 - Bucşa paletei; 4 - Arbore;
5 - Răcitor cu ulei; 6 - Multiplicator 1:60; 7 - Frână mecanică; 8 - Macara cu cărucior; 9 - Convertor;
10 - Traductor de viteză; 11 - Transformator; 12 - Pală; 13 - Lagărul palei; 14 - Sistem blocare rotor;
15 - Unitatea hidraulică; 16 - Fundaţie; 17 - Reductorul sistemului de viraj;
18 - Cuplaj disc; 19 - Generatorasincron; 20 - Ventilatorul generatorului

Fig. 4.29. V80 turbine with multiplier and asynchronous generator.

2. new construction concepts adapted for rotor manufacturing;

3. large-scale use of carbon fibre for the construction of high-power turbine blades;

4. flexible rotors placed behind the tower with small thermal solidity coefficient;

5. direct coupling, new topologies of permanent magnet generators;

6. studies of 5 MW turbines design;

7. variable speed rotor, high voltage generation;

8. studies of the development of offshore turbines: high rapidity coefficient turbine, special foundations and structures, floating turbines, hydrogen production and transportation, special lifting systems, etc.;

9. design and testing of wind turbines with rated power of 8-12 MW per unit [25], work started in 2005 and to be completed in 2009. 12 MW turbine diameter shall be 190 m, tower height - 170 m.

Table 4.3 presents the main characteristics of marketed wind turbines with power over 1.0 MW [26-33]. The symbols mean:

P_n - rated power; D_R – rotor diameter, H_T - tower height, n - nominal rotation speed, γ - range of rotational speed variation;

AG - asynchronous generator; RA*G* - ring asynchronous generator, DFAG - dual feed asynchronous generator, PMG - permanent magnet generator;

U - multiplier gear ratio, V_P - starting wind speed, V_n - wind rated speed (calculation value); ? - lack of data.

The largest 5 MW wind turbine, developed by the German Repower Company [30], was put into operation in August 2006 in the coastal area of the North Sea. It is the first pilot wind farm structure located near the "*Beatrice*" oil platform (Fig. 4.30).

Based on Table 4.3 data the following conclusions can be drawn:

1. there is a clear trend for the use of power adjustment through changing the pitch control, which allows a finer control of power supplied into the grid and reduction of mechanical loads (p. 5.3);

2. asynchronous generators with constant rotation speed are being replaced with dual power;

3. asynchronous generators or permanent magnets synchronous generators. In both cases the rotor speed is variable;

4. for moderate climatic conditions turbines with lowest starting and rated speed are suitable, for example: D6, E82, FL2500, N100/2.5, designed for areas with moderate wind speeds.

Fig. 4.30. Mounting of 5 MW wind turbine, Germany, North Sea coast

The need to adjust the rotation speed of the turbine results from Figure 4.31, which depicts the $P_r(\Omega_r)$ characteristics for different wind speeds: wind velocity brings variation of the maximal (optimal) power produced by the rotor. To

Table 4.3. Main characteristics of modern turbines, over 1,0 MW power

Turbine type, country	P_n	D_R / H_T	n / γ	Generator type	U	Power adjustment	V_P / V_n
	MW	m	rot/min	–	–	–	m/s
D6,Germany	**1,25**	**64/60–91**	**21,1/13,2–24,5**	**GADA**	**1:53,1**	**Pitch**	**2,8/12,5**
V82-1,65, Denmark	1,65	82/78	14,4/0,0	GA	?	Stall	3,5/13,0
Z72, the Netherlands	2,0	72/86-80	23,5/?	GMP	1:1	Pitch	3,0/15,0
E-82, Germany	**2,0**	**82/70–138**	**?/6–19,5**	**GMP**	**1:1**	**Pitch**	**2.0/12,0**
V-90-2, Denmark	2.0	90/80–105	14,9/9,0–14,9	GA	?	Pitch	2,5/13,0
D8,Germany	2,0	80/80–100	18,0/11,1–20,7	GADA	1:94,4	Pitch	3,0/13,5
E-70, Germany	2,3	71/58–119	?/6,0–21,5	GMP	1:1	Pitch	2,0/15,0
FL2500, Germany	**2,5**	**100/65–160**	**?/9,4–17,1**	**GAI**	**1:79,6**	**Pitch**	**3,5/11,5**
N100/2,5 Germany	**2,5**	**100/100**	**?/9,6–14,9**	**GADA**	**1:74,4**	**Pitch**	**3,0/12,5**
V90-3, Denmark	3,0	90/80-105	16,1/8,6-18,4	GA	?	Pitch	4,0/15,0
E-112, Germany	4,5	114/120	?/8,0-13,0	GMP	1:1	Pitch	2,5/?
5M,Germany	5,0	126/100-117	?/6.9 – 12.1	GADA	1:97	Pitch	3,5/13,0

extract maximal power from the wind it is necessary to change the rotation speed Ω_r so as to maintain the operating point of the turbine in the optimal (see the red line) field. Below (Fig. 4.32 - 4.34) there are three of the most frequently used generator-public electricity grid connection schemes, which differ by the generator type:

- rotor-short-circuit asynchronous generator;
- ring- and dual feed asynchronous generator;
- permanent magnet- and turbine rotor directly connected synchronous generator.

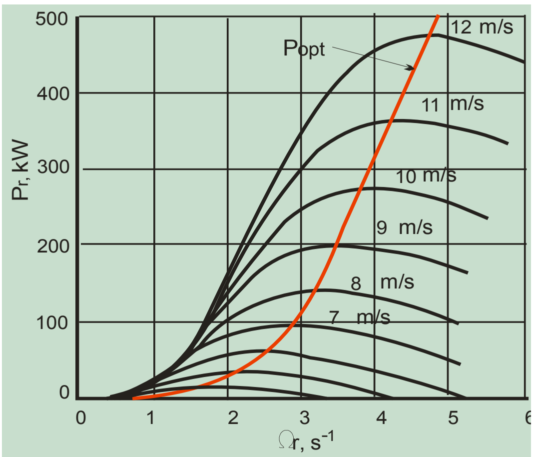


Fig. 4.31. Rotor power variation due to rotation speed and wind velocity

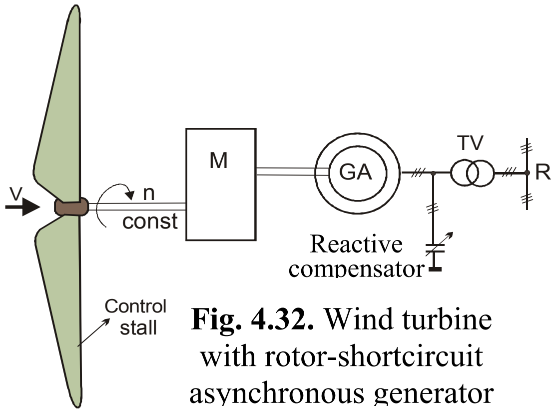


Fig. 4.32. Wind turbine with rotor-shortcircuit asynchronous generator

Advantages:

1) simplicity, reliability and low cost;
2) advanced technology.

Disadvantages:

1) constant speed;
2) significant mechanical loads;
3) power pulses are transmitted into the network;
4) multiplier required.

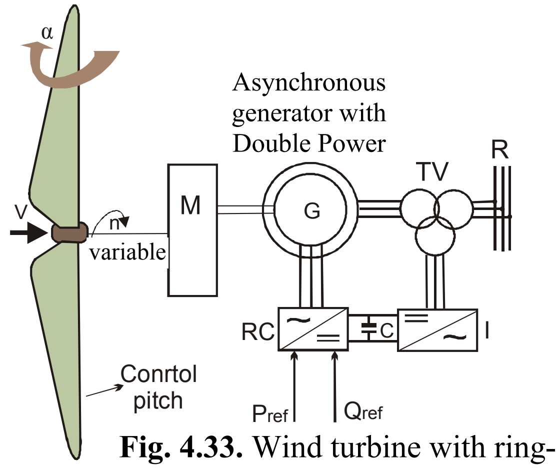


Fig. 4.33. Wind turbine with ring- and dual feed asynchronous generator

Advantages:

1) variable speed from 50 to +30% around synchronous speed;
2) controlled rectifier- *RC* and inverter *I* power does not exceed 30-35% from the generator power;
3) control of active P_{ref} and reactive Q_{ref} power.

Disadvantages:

1. slip rings;
2. multiplier required (increase of losses and maintenance costs).

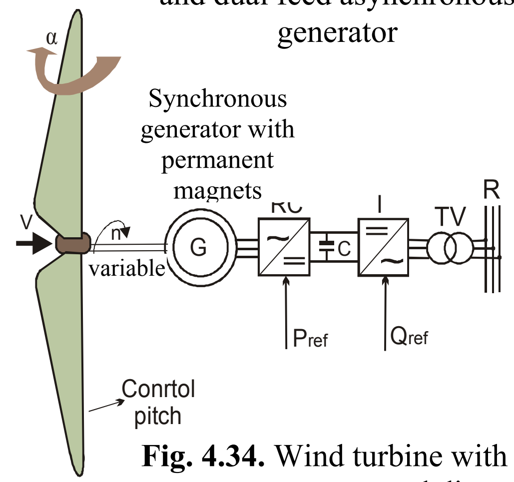


Fig. 4.34. Wind turbine with permanent magnet and direct coupling synchronous generator

Advantages:

1) variable speed for the whole range required;
2) does not require rings and brushes;
3) control of active P_{ref} and reactive Q_{ref} power;
4) high efficiency;

Disadvantages:

1. controlled rectifier- *RC* and inverter *I* power is equal to the generator power;
2. multipolar generator has large sizes and weight;
3. requires permanent magnets for excitation.

6.2. Wind farms

Fig. 4.35. Wind farm located on the hills of Challicun, Australia [31]

Large scale wind energy production is done by tens or hundreds of wind turbines forming the so-called "wind farms" or wind plants, connected to the public electric grids. Synchronous operation mode employing traditional generating units is beneficial for wind energy producer: all energy produced is supplied to consumers connected to the same public electric networks. At speeds below 3 m/s or when the wind is missing, the energy producer becomes a consumer. Medium and high power wind turbines are not operated in autonomous regime due to the high cost of electric batteries. In this case, wind turbine operation in parallel with an electric unit is rational. Such schemes are common in Africa, South America, China, India, where there are isolated areas not connected to the public electric grids. Figures 4.35 and 4.36 are examples of wind farms located on hills.

Fig. 4.36. Wind farm on a hill, California, USA [32]

7. Small power wind turbines

7.1. Global market overview, manufacturing companies and incentive policies

Small systems for wind energy conversion were among the first used by humans for their own or community energy needs. Further over-centralisation of power distribution system led to a substantial costs increase in the case of isolated consumers. From this point of view, the idea to de-centralize power supply systems for isolated consumers is appropriate.

It is noticeable that most of the Third World countries do not have centralized electricity distribution networks. Therefore, the area of small power wind turbines tends to enlarge, especially with account of the inevitable fuel costs increase and environmental issues the mankind is challenging. In this case, the state policy promoting green energy production is of major importance. The USA, pioneer of small wind industry, adopted for this purpose in 1985 an incentive system for green wind energy production, which, since 1990 recorded an annual 14-25% increase. About 30% of federal investment tax credit will bring an annual 40% growth of small power wind turbines sales [34]. About half of small power wind turbines manufactured in USA were exported, and this shows that the small wind turbine industry is one of the dominant renewable energy technologies in the US.

The term *"small power wind turbine"* is defined as an electricity generator with up to 100 kW capacity. A small wind system can include, if necessary, a turbine, a tower, an inverter, batteries, foundation, etc. To examine what the market for small power wind turbines in the US is about, one should consider the following. According to [41], the number of small wind turbines sold in the US in 2006 was 6807 units, of which 6639 (about 98%) produced in the USA, with a total installed capacity of 17543 kW (including 16093 kW of US produced units). In 2006 outside US, 9502 turbines were sold having a total installed capacity of 19483 kW [35]. The correlation analysis of turbines connected to the network and installed separately (Table 4.4) shows that the great majority (5933 to only 706) of turbines are not connected to the network, thus they are employed by isolated consumers.

The cost of small wind turbines remains the only major factor affecting the market growth. For small wind turbines, the generation volume is not the only question, the increasing costs of construction materials, such as copper and steel, also has to be considered. Market growth is also a major function of state policies in the field, particularly regarding ways to exempt companies of various taxes [36], other financial incentives, etc.

Table 4.4. Analysis of ways to install small wind turbines

Connection type	**Units**	**Installed capacity, kW**	**Sales, USD**
Network	706	5158	18197600
Isolated	5933	10935	32706750
Total	**6639**	**16093**	**50904350**

Another impediment is the investment payback period. In the USA, for small wind turbines this period ranges from 6 to 30 years, depending on many factors, such as the quality of wind resources, installation site, turbines purchase costs, turbine performance and energy costs. A study conducted in 2006 at Lawrence Berkley National Laboratory estimated that 30% decrease of the federal investment tax credit will reduce turbines payback period to approximately 4,5 years, and, similarly, exemption of the state property tax can reduce this period to 4 years [36]. This case is similar to photovoltaic systems industry, whose market grew due to federal investment tax credit, thus helping consumers to purchase solar systems.

The demand for small wind turbines arises from consumers' interests with regard to climate change, unpredictable gas prices and energy security. Many consumers, representing nowadays a small percentage of the market, are driven by the decision or need to meet energy needs independent of the electric network.

The analysis of the impediment factors on small wind turbine market is presented in Table 4.5, based on a 72 respondents' survey. The answer to each of the 10 questions was appreciated by an 8-degree scale (1 - no barriers, and 8 - greatest barriers).

The top export markets for US producers are Canada, UK, China, Europe (excluding UK) and India. Table 4.6 presents applications of turbines sold in 2006. Most small power wind turbines (80%) are used for lighting and heating rural and suburban houses, for farms irrigation and other works, for small businesses electricity supply (mainly for processing and storage of agricultural production) located in areas without electricity networks, etc.

Table 4.5. Small wind turbine market growth barriers

Indicator	1	2	3	4	5	6	7	8	Average
Economic/buyer's price									6,53
Restrictive areas and permission rules and/or costs									6,03
Lack of support incentives and/or of significant subsidies									5,35
Lack of financial incentives									5,73
Visual impact/community opposition									5.14
Lack of public information /awareness									5,00
Lack of turbine certification									4,87
Lack of installer certificate									4,42
Lack of access to information regarding wind resources and maps									4,19

Table 4.6. Small wind turbine application areas

Application	Area
Rural or suburban houses	51%
Farms	19%
Small businesses	10%
Schools or public facilities	10%
Urban use	5%
Other	5%

The growth of wind turbine market is driven by cost reduction of 1 kWh of electricity produced, which decreased from 0.15-0.18 USD/kWh to 0.1-0.11 USD/kWh in order to achieve 0.07 USD/kWh over the next five years. For comparison, electricity currently produced by big wind turbines is 0.04-0.07 USD/kWh and by solar modules - 0.18 USD/kWh [37]. Estimates were made according to 2004 data, which include federal policies for commercial systems and federal investment tax credit. The cost of electricity for high power turbines includes the federal tax credit of 0.02 USD/kWh. According to AWEA 2005, after reducing the production costs by 20% until 2010, the cost of installed capacity kW will reach 1700 USD. The US estimates for the potential market of wind systems indicate that the number of small wind turbines could reach between 4 and 8 million units.

Conclusion: consumer prices and state policies are the most important components in supporting and developing the small power wind turbine market. Geopolitical, climate and economic forces shall further increase the market demands.

Producers of small wind turbines. In the context of action taken to solve the imminent energy crisis, to stop the global environmental impact and the trend towards decentralization (especially for isolated consumers) of power supply and of other types of energy, the small wind turbine industry is continuously growing. Presently, in the world there are a number of companies producing a wide range of small wind turbines rated less than 1 kW and up to 100 kW. The USA became the largest producer of small wind turbines. The American Wind Energy Association (AWEA) has made a compilation of companies manufacturing and selling wind turbines for residential applications, industrial/commercial and farms use (Table 4.7).

Table 4.7. USA companies producing small wind turbines

Producing company	Models (capacity)
Abundant Renewable Energy www.abundantre.com	AWP 3.6 (1 kW)
Bergey Windpower Co. www.bergey.com	BWC XL.1 (1 kW), BWC EXCEL (10 kW)
Distributed Energy Systems www.distributed-energy.com	NPS 100 (100 kW)
Energy Maintenance Service www.energyms.com	E15 (35 kW or 65 kW)
Entegrity Wind Systems www.entegritywind.com	EW15 (50 kW)
Lorax Energy www.lorax-energy.com	FL 25 (25 kW), FL 30 (30 kW), FL 100 (100 kW)
Solar Wind Works www.solarwindworks.com	Proven WT600 (600 W), WT2500, (2.5 kW) WT6000 (6kW), WT15000 (15kW)
Southwest Windpower Co. www.windenergy.com	AIRX (400 W), Whisper 100 (900 W), Whisper 200 (1 kW), Whisper 500 (3 kW)
Wind Turbine Industries Corp.www.windturbine.net	

Small wind turbines produced in the USA are currently employed in over 140 countries. For example, Fig. 4.37 presents the most popular product of the company Bergey Windpower Co. - Bergey Excel-S 10 kW turbine, with a cost of 21450 USD [38].]. Following the adoption of new incentives, the payback period is 6-7 years in California. From a financial standpoint it is net superior to purchase a wind turbine than to purchase electricity from an energy company. Important is that the company developed a set of new very high resolution wind maps for the entire state of California. Similar results have other US companies included in the above table. There are also many other companies in various countries that manufacture and operate small wind turbines. The most known are:

Fig. 4.37. Bergey Excel-S, 10 kW turbine [38].

- Iskra Wind Turbine Manufacturers Ltd, Nottingham, United Kingdom;
- WestWind, J.A. Graham Renewable Energy Services, Northern Ireland;
- Gazelle Wind Turbines Ltd, UK;
- TairuiWindpower CO, China;
- Shenzhen Lemon Digitals Limited, China;
- HEFEI HUMMER DYNAMO CO, LTD, China.

Further, a brief analysis of wind turbines manufactured by the mentioned companies comes.

Iskra Wind Turbine Manufacturers Ltd [39], Nottingham, UK. Iskra wind turbines are some of the most efficient and cost-effective small wind turbines on the market. The manufacturing company has become a reliable supplier of small wind turbines on the European market. The company has full support of Nottingham City Council, which promotes the "*green energy*" and environmental

Fig. 4.38. Iskra AT5-1 wind turbine installed near the Redland school, UK [39]

protection policy, implemented also in schools. Fig. 4.38 presents an image of Iskra AT5-1 turbine installed in 2005 at a school in Redland, UK under a program of CO_2 emissions reduction. The turbine has a three blade rotor mounted on a 12 m tower. It is connected to the network. This is important both economically and environmentally, and also educationally, as part of an educational program to inform the community about opportunities for using alternative energy sources.

WestWind, J.A. Graham Renewable Energy Services [40] is located in Northern Ireland and since 1983 has produced thousands of wind turbines rated 3, 5, 10 and 20 kW, installed worldwide and operating in severe weather conditions. 10 kW turbine is designed to supply small communities. It can be installed in one or more units in one place (in case of high demand for electricity). Fig. 4.39 presents the picture of two wind turbines installed (with a solar installation) at Euda wind farm (Australia). The turbine has a 3-blade rotor and 6.2 m diameter, starts at 2 m/s speed. The rotor speed varies within 110-600 min^{-1} and is equipped with an automatic protection against excessive wind speed. The cost of turbine (without batteries) is $ 53,820.

Fig. 4.39. Two WestWind 10 kW turbines installed at Euda wind farm (Australia) [40]

Gazelle Wind Turbines Ltd, UK [41] was founded in 1998 when the MKW group, responsible for research within North Energy Associates, pointed a market niche for small and medium wind turbines. The prototype turbine was developed with the assistance of the Department of Labour and Industry SMART, UK. Gazelle turbine represents an elegant energy solution for small and medium consumers, such as schools, small businesses, rural companies, water pumping and eco-centres. Its 11 m carbon and epoxide fibre rotor, through a two-stage planetary multiplier, drives the 4-pole generator at 1500 min^{-1}, generating 20 kW of electricity (Fig. 4.40). The turbine is connected to

Fig. 4.40. Gazelle 20 kW wind turbine, installed at Sunderland

Fig. 4.41. 10 kW Tairui wind turbine.

Fig. 4.42. Grassland Well model wind turbine, China.

the network. At 6,5 m/s wind speed and 13 m tower it is designed to generate approximately 60 MW per year. Electricity is standard - 3 phases 400/415 volts, nominal frequency - 50 Hz. Due to its new director Ken Chaplin, Gazelle company today is well positioned for growth in this vibrant sector.

TairuiWindpower CO [42] is a leader in the production of small wind turbines in China. Wind turbines have a power ranging 200-20000 W and are exported to many countries around the world, partly solving the problem of carbon emissions mitigation. The company offers quality wind turbines at relatively low prices. The wind turbine shown in Fig. 4.41 includes a three blade rotor made of rubber-based composite material. Starting speed is 2,5 m/s, calculated speed - 11 m/s. Number of rotations - 160 min^{-1}. The rotor is connected directly to a permanent magnet 10 kW generator, current's voltage - 240 V. Turbine weight is 540 kg. Turbine cost (without batteries) is $ 9,708.

Hefei Hummer Dynamo CO, Ltd is another company manufacturing small wind power turbines in China [43], located in Hefei, the National Modern Technologies Development Zone. The company specializes in research and development, production and promotion of small wind turbines. The steppes located in northeast China are rich in wind energy. Wind power density is usually 200-300 W/m^2. A three blade turbine with 5 m diameter (fig. 4.42) can cover electricity needs of an isolated consumer, including a refrigerator or a pump.

7.2. Small power wind turbines designed at the Technical University of Moldova

Small wind turbines should be mostly robust and simple, have maximal resistance and little maintenance, and optimal wind energy conversion efficiency. Given the topical interest and relatively high costs of imported wind turbines, a team of authors developed two types of small power wind turbines. The wind turbines with servo motors have the ability to track wind direction and remove the bladed rotor out of the wind action at wind speeds exceeding 15-25 m/s. The advantages of these turbines compared to vane wind turbines are:

- angular positioning stability of the bladed rotor at dynamic fluctuations of air currents direction;
- bladed rotor protection from overloads, caused by wind speeds exceeding the highest allowed values.

7.2.1. Wind turbine with tail vane: author development

Based on the study of wind energy potential and specific orographic terrain surface of Moldova, characterized mainly by gorges oriented along North-South direction, the authors developed the concept of a three-bladed rotor with asymmetric aerodynamic profile [44-52]. Theoretical research on the developed rotor was carried out using modern software ANSYS CFX5.7 and Autodesk MotionInventor. As a result, the basic parameters of the aerodynamic profile characterizing the efficiency of wind energy conversion by the rotor blades were determined.

Taking into account that across the gorges the wind prevails on North-South direction with minor fluctuations, the authors have designed a prototype wind turbine facing the wind by means of a vane. This turbine has a simple construction and requires neither cinematic wind guidance devices nor devices for the protection of turbine rotor from the excessive wind action. Construction simplicity of the wind turbine with vane leads to about 20-30% cost reduction compared to turbines with cinematic guidance devices. Fig. 4.43 presents a 3D model of rotor and vane wind turbine having certain parameters (Table 4.8).

The choice of three blade rotor scheme provides a greater dynamic stability, minimizing related vibrations and sonic background, thus resulting a longer life period of all components. Direct connection of the rotor to the generator ensures rotor start up at lower wind speeds, production of a larger amount of energy, requires less demanding maintenance compared to turbine multiplier case. Specially designed permanent magnet generator combines efficiency with the simplicity of construction. The outer coverage of blades featuring asymmetric aerodynamic profile, also the gondola cone and the vane are manufactured from composite materials reinforced with glass fibre employing modern technologies in the CESCER laboratory, TUM:

- MEKP solidifier (methyl-ethyl-ketone-peroxide);
- Luperox K1 Standard, ATOFINA, France;
- CRYSTIC polyester resin;
- Gelcoot (white and black colours);
- Glass fibre.

Table 4.8. Basic parameters of the vane wind turbine.

Parameters	
Bladed rotor diameter	8,6 m
Rotor swept area	58 m^2
Number of blades	3
Blades profile	aerodynamic asymmetric
Rated power at wind speed of 10 m/s	10 kW
Wind guidance	vane
Blades positioning	fixed
Voltage	240 V c.c.
Starting wind speed	2 m/s
Calculated wind speed	10 m/s
Generator	three-phase, permanent magnet
Generator drive	direct
Rotation speed, rot/min^{-1}	160
Blade material	composite based on glass fibre-reinforced resin
Turbine weight	335 kg
Variable height modular telescopic tower	7 - 18 m
Modular tower weight	650 kg
Accumulator battery	12V, 200Ah x 20

- Scrint Gobain Vetrotex;
- Woven Rowind;

- Spray Up Rowind;
- Aluminium Hydroxide ATH;
- Polyurethane glue IMFI (France).

The manufacturing technology for blade covering, vane and gondola cone

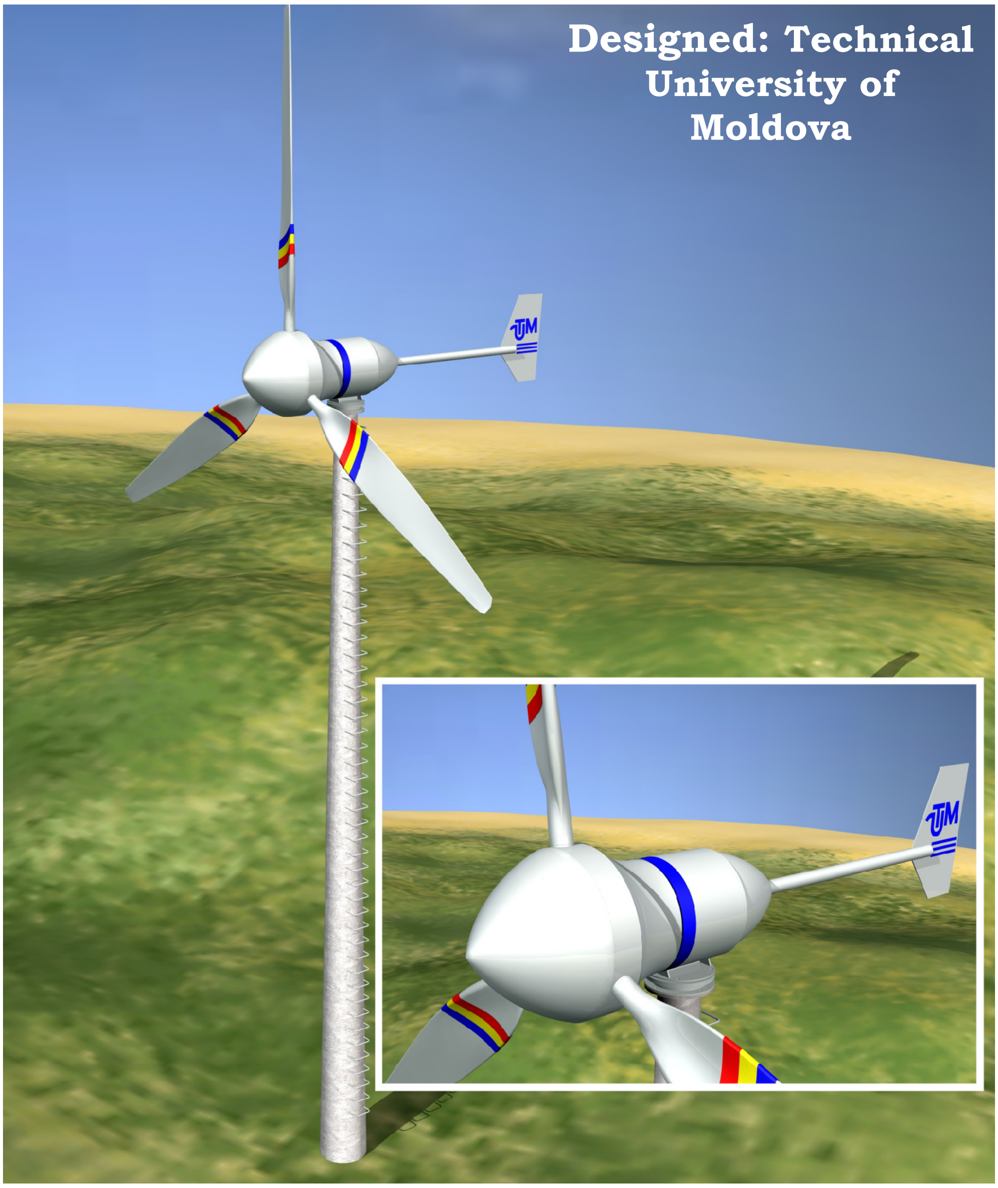


Fig. 4.43. 3D model of rotor and vane wind turbine.

is similar to that of the blades for multi-blade rotor of micro hydro power plants described in Chapter 3, p.5.12. Fig. 4.44 shows the gondola cone and blades fabrication.

Composite materials components resistance is comparable to that of the metal structures and has competitive properties advantages such as small weight, corrosion resistance, fatigue resistance, low starting torque, and relatively low costs of small series production.

The CESCER Laboratory at TUM is endowed with modern equipment, fully fitted for the production cycle of composite materials machine parts using modern technologies. IT-supported technological and infrastructural equipment provide mobility and diversity in terms of timely implementation of various technical and technological solutions, as well as design and research solutions in the field of machine building.

a. ***b.*** ***c.*** ***d.***

Fig. 4.44. Blades (a,b) and gondola parts (c,d) manufacturing from composite material in the CESCER Laboratory, TUM

7.2.2. Wind turbine equipped with servo motor, author development

The wind turbines with servo motors have the ability to track wind direction and remove the bladed rotor out of the wind action at wind speeds exceeding 15-25 m/s. The advantages of these turbines compared to vane wind turbines are:

- angular positioning stability of the bladed rotor at dynamic fluctuations of air currents direction;
- bladed rotor protection from overloads, caused by wind speeds exceeding the highest allowed values.

Fig. 4.45 shows a 3D model of a rotor and an overview of the servo motor wind turbine, developed by a team of authors. Both wind direction rotor orientation and its removal out of the action of air currents is done by means of a device, called servo motor, which performs the kinematical liaison of gondola 1 with tower 2 and which is controlled by a wind vane electronic transducer 3. When the wind direction is changed the vane 3 performs an angular re-positioning, a deviation signal occurs and the control system starts the servo motor, that rotates gondola with rotor in one direction or another until the rotor axis coincides with the direction of air currents. Angular positioning stability is ensured by a certain time delay of the servo motor switch depending on the wind flow action in one direction or another. Repositioning period of bladed rotor perpendicular to airflow velocity vector depends on the kinematical characteristics of the driving mechanism (the servo motor), and actually determines time repositioning stability of the gondola. Kinematical characteristics of the servo motor were determined by the dynamics of the airflow velocity vector variation.

The wind turbine project, developed by authors, was implemented at the Scientific Technical Centre for Implementation of Advanced Technologies at the Technical University of Moldova in cooperation with companies INCOMAS SA, Chişinău, ELECTROMAŞ SA, Tiraspol, Reupies SRL and SA Topaz from Chişinău etc. Fig. 4.46 presents the assembling stage of the component of the wind turbine. The team developed the manufacturing technology for blades and gondola parts from composite material reinforced with glass fibre. The rotor blades and gondola cone were made of composite materials in the Laboratory of New Technologies within the Centre for Renewable Energy Conversion Systems Development (CRECSD), Technical University of Moldova. The wind turbines with servo motor, shown in Fig. 4.47, are installed at the Râşcani campus of the Technical University of Moldova and is designed for lighting and irrigation system of the adjacent dendrologic park.

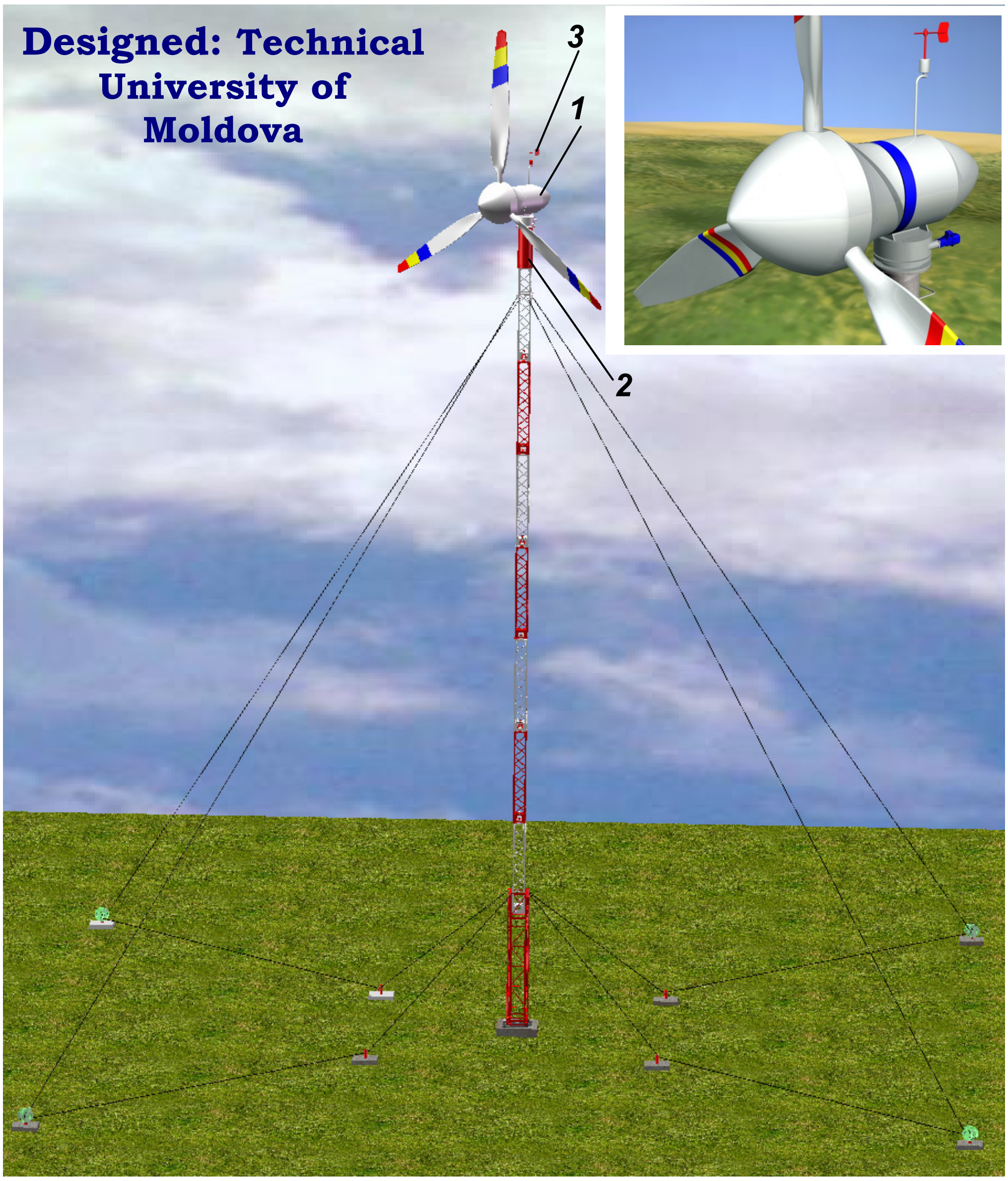


Fig. 4.45. Servo motor wind turbine 3D model

By installing a wind turbine in the park of the Technical University of Moldova, the designers have pursued a specific educational purpose for the student community: the opportunities of using the "*green energy*" without negative impact on the environment.

a. ***b.***

a. ***b.***

Fig. 4.46. Assembling stage of the component of the wind turbine.

a. ***b.***

Fig. 4.47. Wind turbine with telescopic tower (a) and tubular (b) mounted at Râşcani campus, TUM, Republic of Moldova.

The wind turbine, developed by authors, was demonstrated at the various International exhibitions [53-60], where was appreciated by gold and silver medals.

Structural and functional parameters of the servo motor turbine are presented in Table 4.9.

Table 4.9. Basic parameters of the servo motor wind turbine.

Parameters	
Bladed rotor diameter	8,6 m
Rotor swept area	58 m^2
Number of blades	3
Blades profile	aerodynamic asymmetric
Rated capacity at 10 m/s wind speed	10 kW
Wind guidance	actuator
Blades positioning	fixed
Voltage	240 V c.c.
Starting wind speed	2 m/s
Calculated wind speed	10 m/s
Generator	three-phase, permanent magnet
Generator driving	direct
Rotation frequency	160 min^{-1}
Blade material	Resin-based composite material reinforced with glass fibre
Turbine weight	392 kg
Variable height modular telescopic tower	7 - 18 m
Modular tower weight	708 kg
Accumulator battery	12V, 200Ah x 20

The electricity generation depend on the turbine power characteristics (Fig. 4.48) and wind speed probability density function. Fig. 4.49 shows the connection schemes of the wind turbine for electricity supply to the dendrologic park lighting system of the Technical University of Moldova. The tower has modular construction with telescopic height advancing, or tubular with special hydraulic device, due to which lifting cranes are not required when changing the turbine installation height.

The chosen construction of the tower ensures the reduction of turbulence induced by the wind passing through the tower. Constructive peculiarities of the turbine correspond to local industry technological possibilities, which fact allowed manufacturing of 75-80% of components at domestic industrial enterprises.

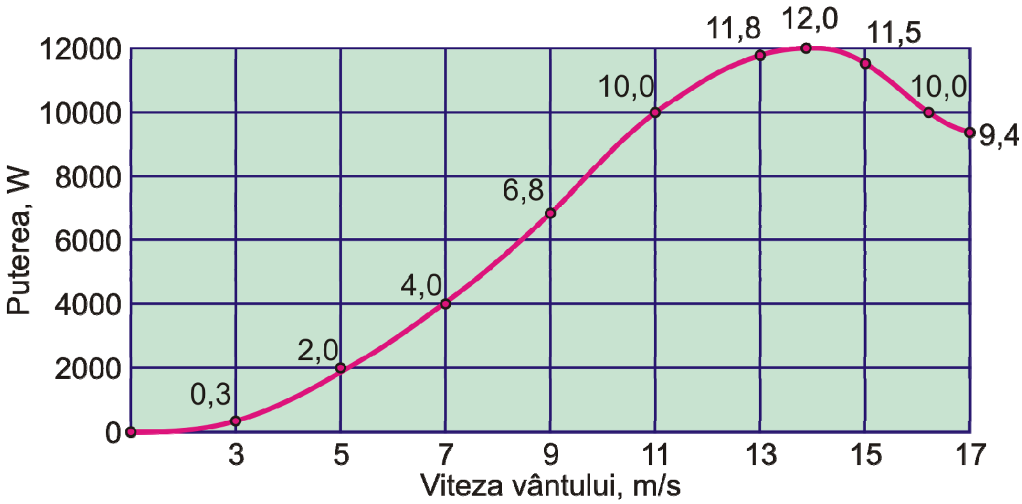


Fig. 4.48. Wind turbine power characteristic

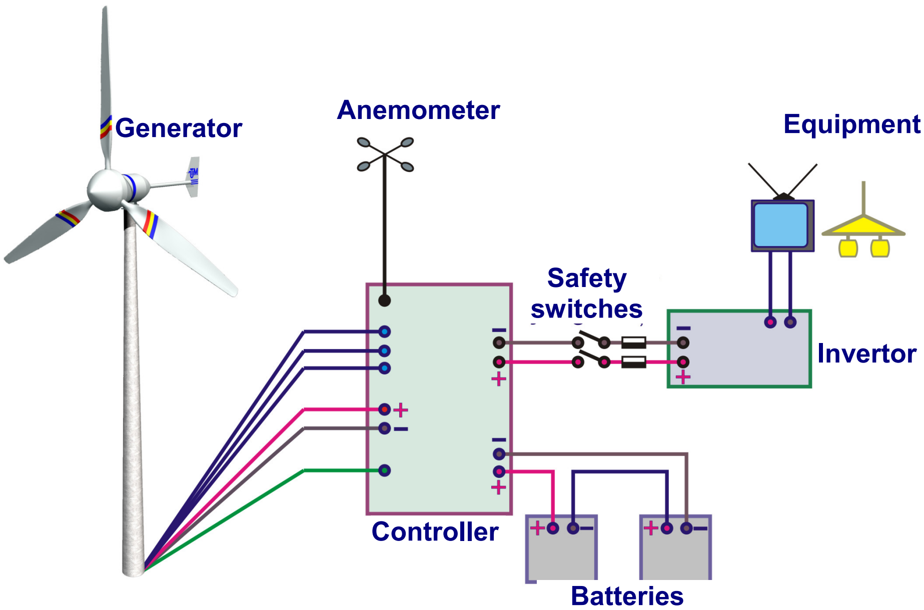


Fig. 4.49. Wind turbine connection schemes for lighting system supply.

7.2.3. Wind energy supply of the dripping irrigation system

The electricity supply of agricultural land irrigation systems from the public power grid becomes inefficient, that is why various autonomous sources of energy are becoming more widespread [7, 50-52]. Fig. 4.50 shows a drip irrigation system powered by electricity from a wind turbine 1 designed by the authors and described in p. 7.2.1 and 7.2.2. Centrifugal pump 2 with productivity parameters Q (m^3/h) and pumping height H corresponding to the needs for irrigation is supplied with electricity from a wind turbine generator 1. Centrifugal pump 2 sucks water from the lake (or river) and pumps it into the system through the fertilizing dispenser 3 and filtering device 4 connected consecutively in the pump discharge pipe. Fertilized and filtered water under

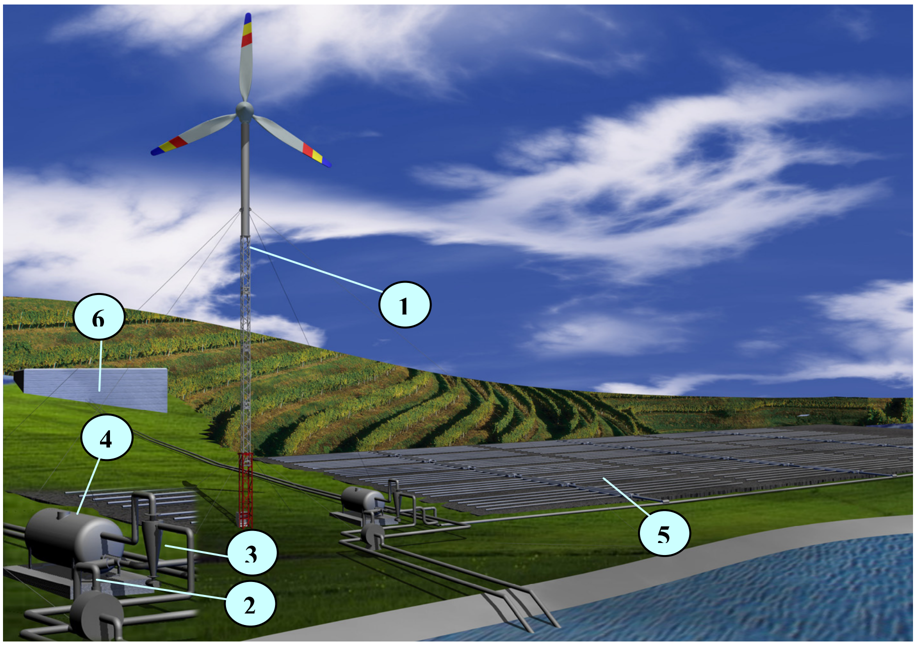


Fig. 4.50. Drip irrigation system powered with electricity produced by the wind turbine.

pressure is pumped into the pipe network 5. The irrigation system must include a water storage tank 6 located at an altitude higher than the irrigated ground. Water in the tank may be used during the periods when the wind speed is insufficient to produce the demanded electricity. Subject to the launch of a new generation of electric batteries on the market, more efficient and cheaper, the irrigation systems equipped with batteries could be an alternative that will load at times when irrigation is not appropriate.

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