DOI: 10.24427/978-83-65596-73-4_3

3. WIND ENERGY

3.1. Introduction

Wind energy is one of the most environmentally friendly energy industries. Wind power is used in more than 70 countries of the world to produce electricity. Wind power plants generate more than 1% of the world's electricity. In 2016, the installed capacity of wind power plants was 466 GW (51.2 GW higher than in 2015). Installed power growth is 12.3% as compared to 18.6% in 2015. In Lithuania wind power generates more than 20% of the country's electricity demand. Wind energy is considered to be one of the most popular renewable energy sources. In countries where this energy is already widely used, the environmental conditions substantially improve. To increase the efficiency of wind power plants (Fig. 3.1) and work reliability, and also to solve other problems, it is necessary to carry out climate research on wind energy and collect information on the distribution of wind energy depending on wind speed profiles, etc.

Fig. 3.1. Photo of wind turbine (Source: photo by K. Jasiūnas)

3.2. Generation of wind energy in Europe

According to the statistics of 2016, the most capable countries of wind energy generation in Europe are: France – 12% (5260 TWh) and Sweden – 12% (5048 TWh). Also capable of wind power energy production are: The United Kingdom – 10% (4409 TWh), Finland – 10% (4418 TWh), Germany – 9% (4017 TWh) and Poland – 9% (3682 TWh).

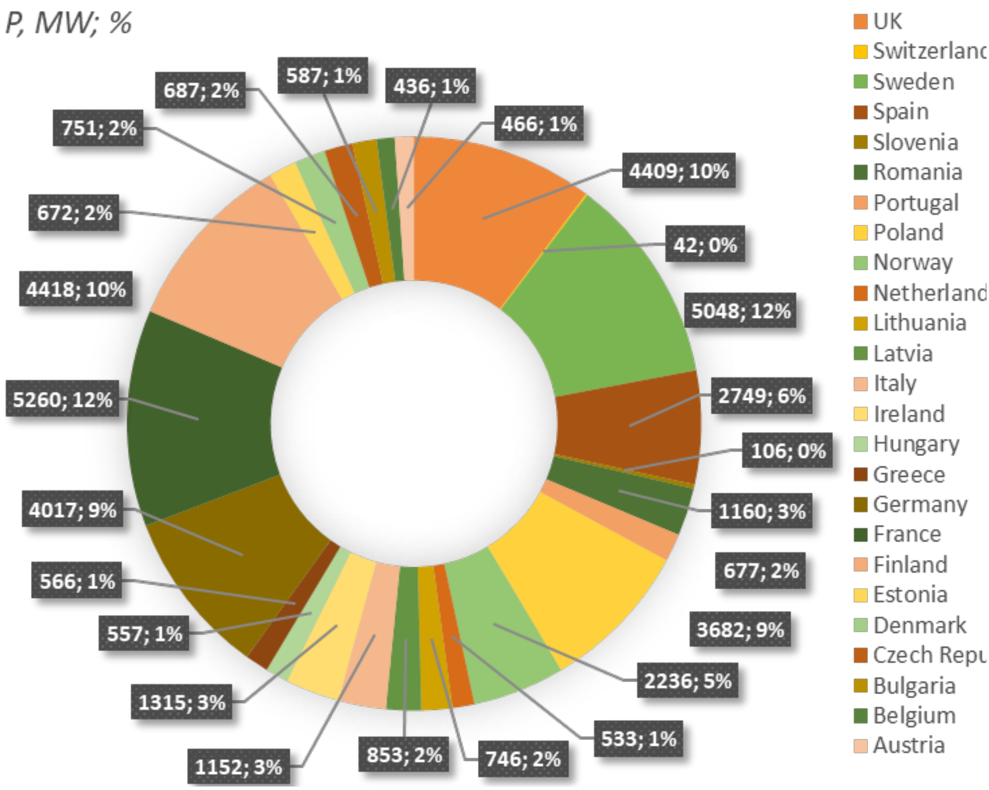


Fig. 3.2. Generation of wind energy in Europe (Source: own elaboration)

3.2.1. Wind energy installed power development in Lithuania

In Lithuania wind energy generation capacity increase is one of the fastest in Europe. The tendency of the last 10-year increase can be expressed by exponential equation (3.1) and developed by geometric progression:

$$P_{windlt} = f(t) = 41.46e^{0.26t}, \text{ where } R^2 = 0.946 \qquad (3.1)$$

Ten years in Lithuania the total wind energy capacity increased by about 10.5 times. In this country wind energy production capacity of 493 MW is the main source of the total energy production together with the reserve of Kruonis Pumped Storage Power Plant (Kruonis PSPP) which works as a hybrid energy production system (Fig. 3.3). At night, when wind turbines generate more power, but the load is smaller, the energy produced by wind turbines supplies energy to the pumps and moves the water to the reservoir of hydro pump storage station.

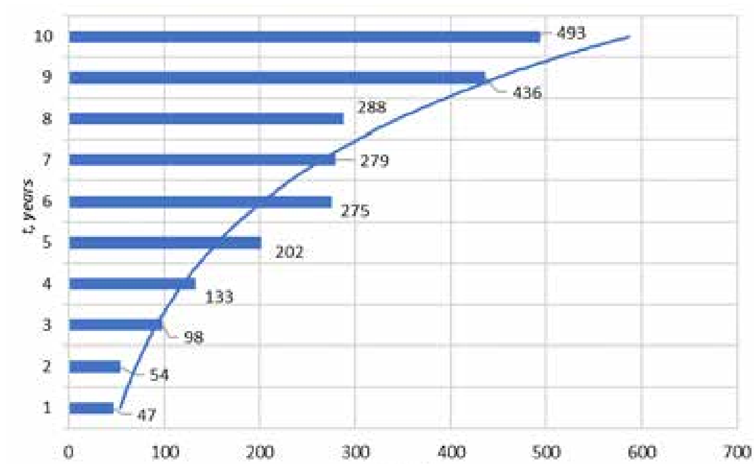


Fig. 3.3. Wind energy installed power development in Lithuania in 2007-2016 (Source: own elaboration)

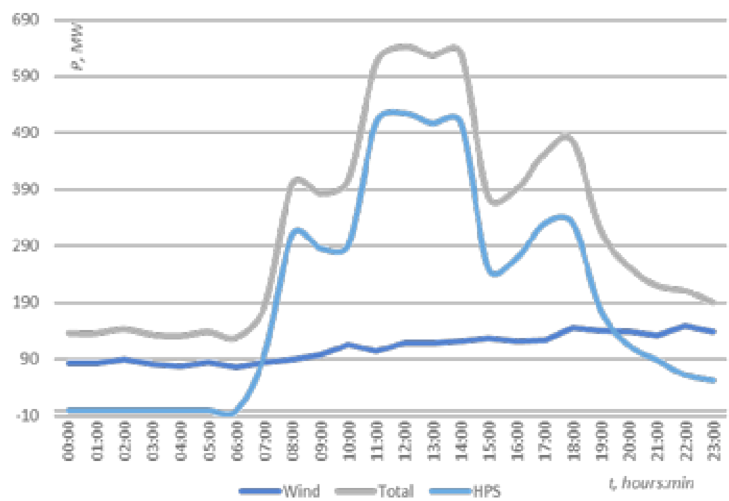


Fig. 3.4. Wind-hydro pump storage system electricity production in Lithuania (Source: own elaboration)

During the daytime wind produces less energy but the load is higher, thus, the hydro pump storage station returns the peak energy, when the energy needs are bigger and the price is higher (Fig. 3.4).

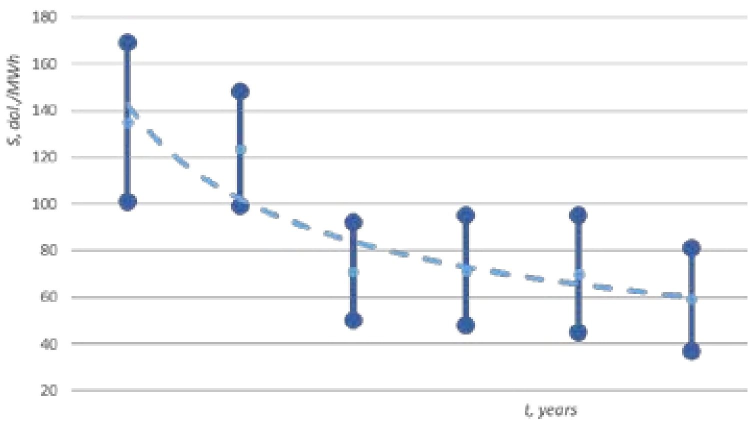
In the period of ten years, the fastest increase of onshore wind energy power production took place in the Eastern European countries where the capacity growth had started from very low values.

3.2.2. Global wind energy price decrease

In other European countries (regions), the wind energy capacity increase begins from higher values and is significantly lower. There is a tendency to increase costs of wind power capacity worldwide and decrease wind energy price (Fig. 3.5). The decrease of the wind energy price can be calculated from below equation (3.2) (by USD per MWh):

$$E_{USD/MWh} = f(t) = 143t^{-0.48}, \text{ where } R^2 = 0.877 \tag{3.2}$$

Reduction of the cost of wind energy generation (Fig. 3.5) shows that this kind of renewable energy becomes more and more competitive as compared with the cost of traditionally produced energy.



	2009	2010	2011	2012	2013	2014
Smin	101	99	50	48	45	37
Smax	169	148	92	95	95	81
Svid	135	123,5	71	71,5	70	59

Fig. 3.5. Global decreasing tendency of the cost of wind power generation in the 2009-2014 period (Source: own elaboration)

From 2009 to 2014, the world minimum price of wind power energy dropped by about 60%, from 100 USD/MWh to approximately 40 USD/MWh (Fig. 3.5, S_{min}). The maximum price of wind power generated electricity was reduced by about 53%, from 170 USD/MWh to 80 USD/MWh (Fig. 3.5, S_{max}). The average reduction of wind power price during the above-mentioned period was about 57%: from 140 USD/MWh to 60 USD/MWh (Fig. 3.5, S_{vid}).

3.2.3. Global tendencies in wind power generation installed capacity development

The global wind power generation installed capacity may be expressed with the tendency of power law increase and can be calculated from the power nature with Eq. (3.3):

$$P_{WW} = f(t) = 86386e^{0.1766t}, \text{ where } R^2 = 0.988 \tag{3.3}$$

The wind power generation installed capacity in Europe may be expressed with the tendency of power law increase and can be calculated from the power nature by the following Eq. (3.4):

$$P_{WE} = 53006e^{0.112t}, \text{ where } R^2 = 0.992 \tag{3.4}$$

Eqs. (3.3) and (3.4) can be used to preliminarily calculate the tendency of wind energy increase in future with 0.98-0.99 probability, in Europe and in the world.

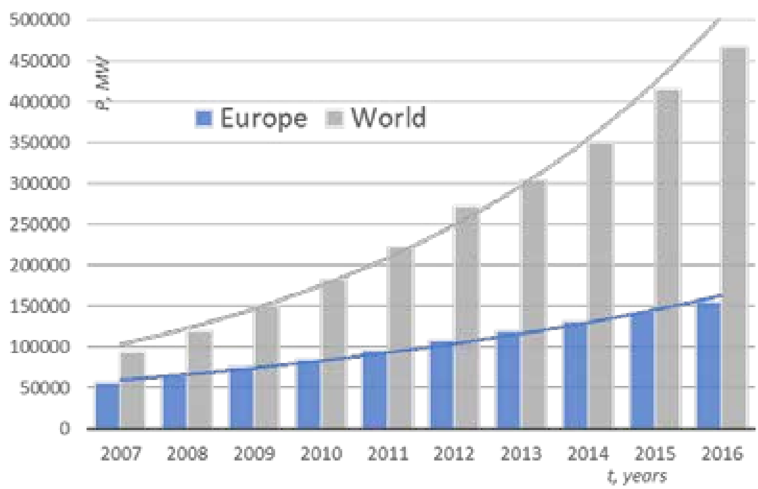


Fig. 3.6. Wind power generation development worldwide in the 2007-2016 period (Source: own elaboration)

The increase of global wind energy capacity from 2009 to 2016 was about fivefold.

During the period of ten years, wind energy capacity was installed about 1.8 times more often in the rest of the world than in Europe. It could be stated that during the discussed period Europe had a leading position in the field of wind energy production, but evidently in terms of the increase of installed power capacity, wind energy production developed faster in the rest of the world.

3.2.4. Development of wind power generation installed capacity in European countries

The comparison of wind energy installed capacity in southern and eastern European countries shows that in 2016 the biggest installed capacity was in:

1) Spain – 22992 MW,
2) Poland – 5807 MW,
3) Portugal – 5304 MW,
4) Lithuania – 493 MW.

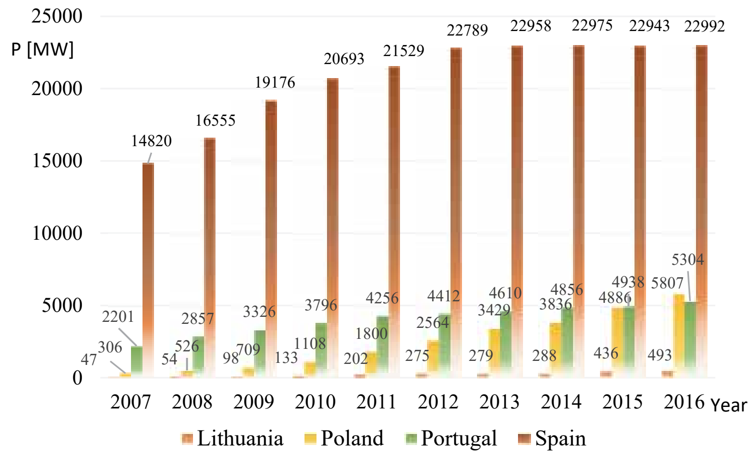


Fig. 3.7. Wind energy installed power development in selected European countries: ten-year tendency (Source: own elaboration)

From 2007 to 2016, in Spain, wind power capacity increased by about 55%, from 14,820 MW to approximately 22,992 MW. During the same period in Poland, wind power capacity increase was about 1795% (about 19 times), from 306 MW to more than 5800 MW. This wind power increase may be the largest in Europe and one of the largest growths in the world. In Lithuania, wind power capacity increased by approximately 950% (about 10.5 times), from 47 MW to 493 MW. For a country with a small economy, it is a significant result, which can influence the overall economy and environmental situation of the country and can be a positive example for bigger economies worldwide in the field of renewable energy development. From 2007 to 2016, in Portugal, wind power capacity increase was more than 140%, from 2201 MW to approximately 5300 MW (Fig. 3.7).

3.2.5. Development of offshore wind power generation installed capacity in the world

The total ten-year increase in the development of the European offshore wind energy production (Fig. 3.8) may be expressed by the following exponential equation (3.5):

$$P_{woE} = f(t) = 889.8e^{0.29t}, \text{ where } R^2 = 0.99 \quad (3.5)$$

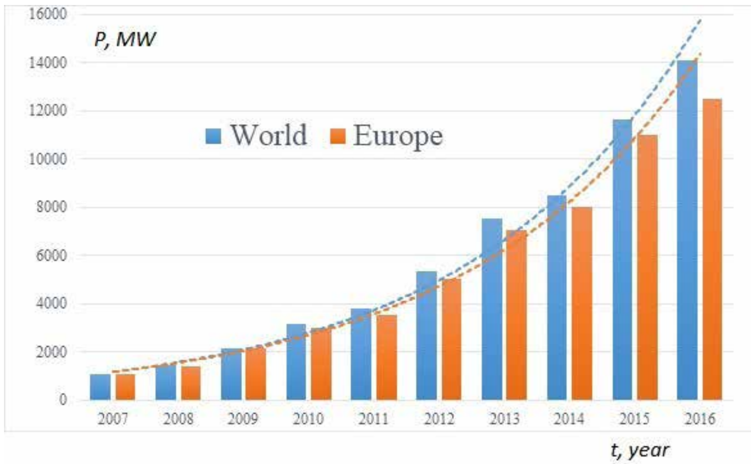


Fig. 3.8. Tendencies in the development of wind energy installed power in the EU and in the world during a ten-year period (Source: own elaboration)

The total ten-year increase in the development of global offshore wind energy production (Fig. 3.8) can be expressed by the following exponential equation (3.6):

$$P_{WOW} = f(t) = 894.6e^{0.28t}, \text{ where } R^2 = 0.99 \quad (3.6)$$

The above equations can be used to predict wind (offshore) energy increase tendencies in future with 0.98-0.99 probability in European countries and worldwide.

3.2.6. Development of offshore wind power generation installed capacity in European countries

The comparison of offshore wind energy installed capacity in European countries shows that in 2016 the biggest installed capacity was in:

1) the United Kingdom – 5150 MW,
2) Germany – 4108 MW,

3) Denmark – 1217 MW,
4) the Netherlands – 957 MW,
5) Sweden – 213 MW.

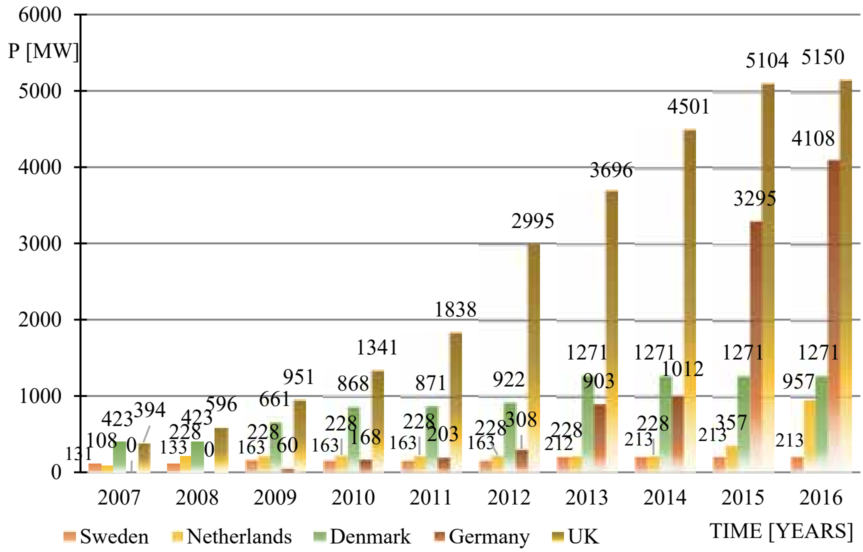


Fig. 3.9. Tendencies in the development of wind offshore energy installed power in European countries during a ten-year period (Source: own elaboration)

From 2007 to 2016, in the United Kingdom, offshore wind power capacity increased more than 12 times: from 394 MW to 5150 MW. During the same period in Germany, offshore wind power capacity increased from 0 MW to more than 4100 MW. This wind power increase may be the largest in Europe and one of the largest growths in the world. At the same time in Denmark, offshore wind power capacity increased approximately 3 times, from 423 MW to 1271 MW. Denmark is a relatively small country, but it is very important as one of the leading countries in the field of wind power energy research and development. Wind energy plays a very important role in the economy of Denmark. Also, in the Netherlands there was a substantial growth in the offshore wind power capacity which increased about 9 times, from 108 MW to approximately 950 MW during the same period. Only in 2016, the growth was by about 600 MW. The largest increase offshore wind energy capacity (2283 MW per year) took place in Germany, in 2015 (Fig. 3.9). According to the provided analysis, it can be observed that Europe is the leading region in the offshore wind energy generation. Europe's and the world's leading countries in the above-mentioned type of energy generation are the United Kingdom, Germany, Denmark, the Netherlands and Sweden.

3.2.7. Main tasks (studies, analyses and activities) before building wind turbines or wind farms

Understand your wind resource

Before the design of wind turbines, a proper place should be selected. In the territory to be selected, the minimum average wind speed should start from 4.5-6m/s throughout the year. The local weather data and wind maps for the potential place should be studied.

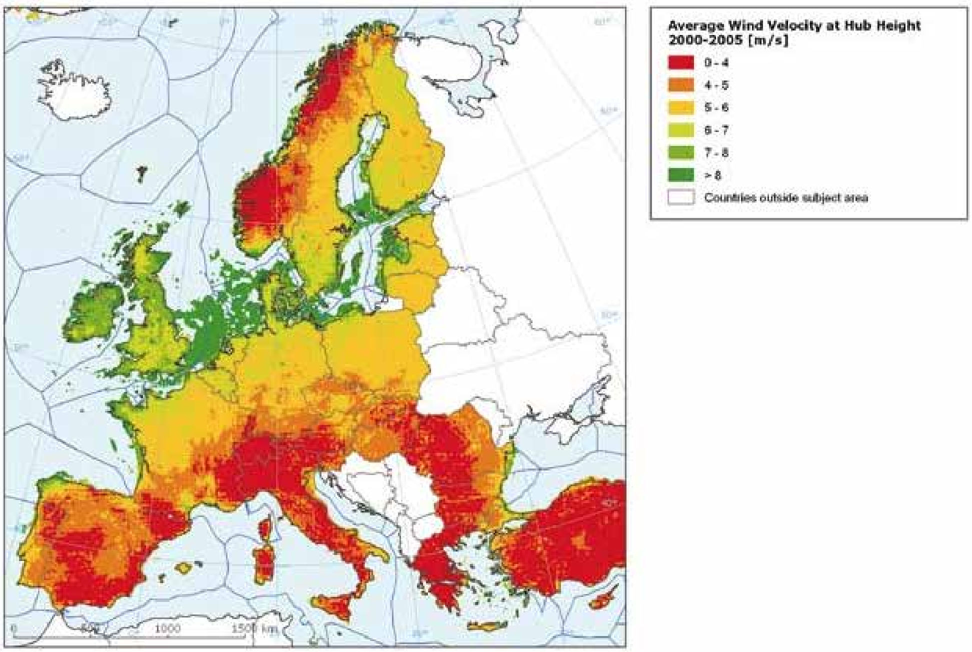


Fig. 3.10. Wind field data after correction for orography and local roughness (80 m onshore, 120 m offshore) in the European Union countries (Source: EEA, 2009)

The wind atlas data (Fig. 3.10) can be used for the wind energy calculation during preliminary evaluation of wind energy resources potential for installation of a wind turbine and wind parks in the selected place and land. More accurate wind energy data can be received in the actual place by measuring and studying the wind speed for several years.

Determine proximity to existing transmission lines

Distribution and transmission lines topology and its availability should be determined. Installation of new high voltage lines can be costly. If possible, the best solution will be the use of the existing transmission and distribution lines (parts of the network). In some cases, wires of higher conductivity could be used.

Secure access to the area

The area should be accessible through roads. In addition, permissions from the landowner should be obtained to make the necessary area (land) restrictions at the time of construction and later, if necessary.

Fig. 3.11. During the construction of a wind turbine, it is necessary to ensure safe storage of expensive equipment (Source: photo by K. Jasiūnas)

Establish access to capital

Building a wind turbine and a wind farm is an expensive project. On average, the development of wind power costs around 1 million Euro per megawatt (MW) of generating capacity installed. Therefore, the developer must secure the flow of sufficient financial resources for installation, commissioning and operation of the wind turbine or wind farm until the generation of revenue.

Identify reliable power network, purchaser or market

Local power purchasers, distributors and transmission networks should be contacted and a survey of the local electricity market power should be conducted.

A

B

Fig. 3.12. Transportation and storage of wind turbine towers during the building of a wind turbine (farm) (Source: photos by T. J. Teleszewski (A) and K. Jasiūnas (B))

Project feasibility considerations

Various other factors need to be addressed before finalizing the location and the technical feasibility. These include impact on endangered or protected species (if any), the site's geological suitability, the influence of noise on the local community, aesthetical issues, local air traffic and other issues related to the site development, such as roads.

Analyse the economics of wind energy

The economic feasibility and payback time should be calculated.

Obtain zoning and permitting expertise

The county, city and the state authorities should be consulted for permitting purpose and any concern should be raised before starting the construction.

Selection of turbine

The selection of turbines should be considered according to the required generation capacity, site-specific conditions, design criteria and costs.

Final evaluations of wind turbine costs

Total costs should be evaluated throughout the period of at least 20 years:
1) purchasing (primary investments) costs,
2) permanent costs,
3) overhauling costs,
4) interruption costs,
5) financing costs,
6) other costs.

Photographs 3.11-3.13 show the stages of a wind farm construction.

Fig. 3.13. Installation of wind turbine elements in a field (Source: photo by K. Jasiūnas)

3.3. Wind farm land area requirements

After finding the land which is preliminarily suitable for wind energy development, the possibility should be carefully analyzed. The primary task for the wind park design is to locate the wind turbines in the best wind sites to maximize energy production. Wind turbines are typically arranged in single or multiple rows, depending on the size and shape of the land. The distance between rows is determined by the relief profile. Multiple rows can be used in a wider and flatter land spaces. The rows should be set as perpendicularly as possible to the dominant wind direction. The main task is to erect the wind turbines so that any interference influences them as little as possible. The interference of a turbine by wind coming from the nearby turbine is called wake effect or array effect. If the turbines are positioned close to one another, they make bigger wake effects and induce energy losses. A big distance between wind turbines maximizes energy production, but increases requirements for cables, as well as land requirements for the infrastructure. Turbine spacing must be optimized to minimize the cost. The optimal distance between wind turbines defined by rotor diameters is depicted below (Fig. 3.14).

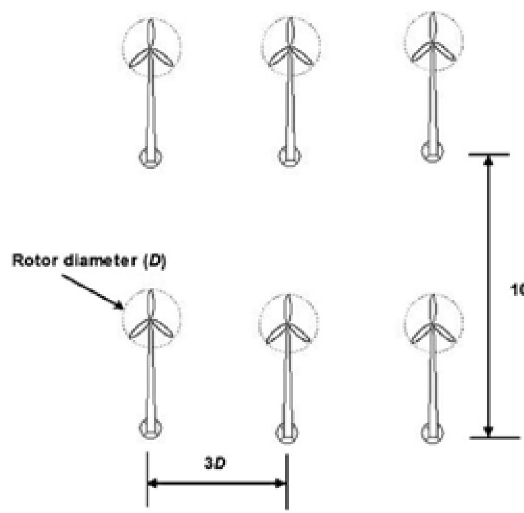


Fig. 3.14. Land space requirement for wind turbines in the wind farms (Source: Ghosh & Prelas, 2011)

3.3.1. Energy and power from wind

Wind blowing power can be generally expressed as the airflow through the wind turbine with speed v, and its kinetic energy may be calculated from Eq. (3.7):

$$E_k = \frac{m \cdot v^2}{2} = \frac{1}{2} \cdot \rho_a \cdot V_a \cdot v^2, \tag{3.7}$$

where:
m – the mass of moving air (kg), ρ_a – density of air (g/m^3), V_a – volume of air (m^3), v – wind speed (m/s).

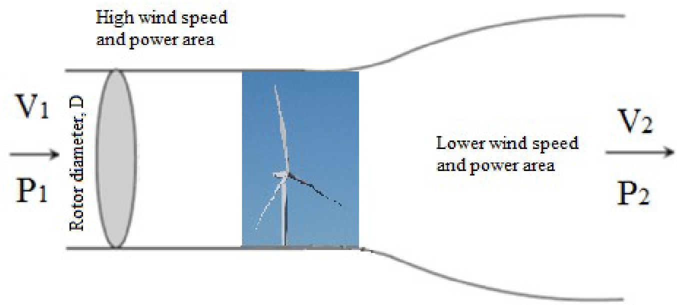


Fig. 3.15. Wind turbine operation principle (Source: own elaboration based on Ghosh & Prelas, 2011)

When the wind crosses the area of the turbine rotor – A_T interacting with air volume, then the power of production will be expressed by the following equation:

$$P = \frac{1}{2} \cdot \rho_a \cdot V_a \cdot v^2 = \frac{1}{2} \cdot \rho_a \cdot A_T \cdot v^3 \tag{3.8}$$

Eq. (3.8) expresses the power of the wind flowing without any resistance. In nature the wind blowing through the turbine blades meets the aero-dynamical resistance. Thus, the actual power that is received from the wind turbine (Fig. 3.15) may be calculated from Eq. (3.9):

$$P_A = (C_P \cdot \varepsilon_g \cdot \varepsilon_b) \cdot \frac{1}{2} \cdot \rho_a \cdot A_T \cdot v^3, \tag{3.9}$$

where:
P_A – power (W), 1000 W= 1kW;
ρ_a – air density (kg/m^3) – 1.225 kg/m^3 at the sea level, it decreases with altitude);
A_T – rotor area (m^2);
C_P – power coefficient of turbine (–);
v – wind speed (m/s);
ε_g – efficiency of generator (–);
ε_b – efficiency of gearbox/bearings efficiency (–).

During the real calculation and design:
C_p – practical value can range between 0.35-0.40;
ε_g – approximately 0.8;
ε_b – the efficiency of gearbox, bearings could be about 0.95 and more.

3.3.2. Betz limit

The maximum theoretical value of power factor C_p is 0.593. This value is called Betz limit and is named to the honor of the German scientist who theoretically proved the limit. The graphical expression of the Betz limit is shown in Fig. 3.16.

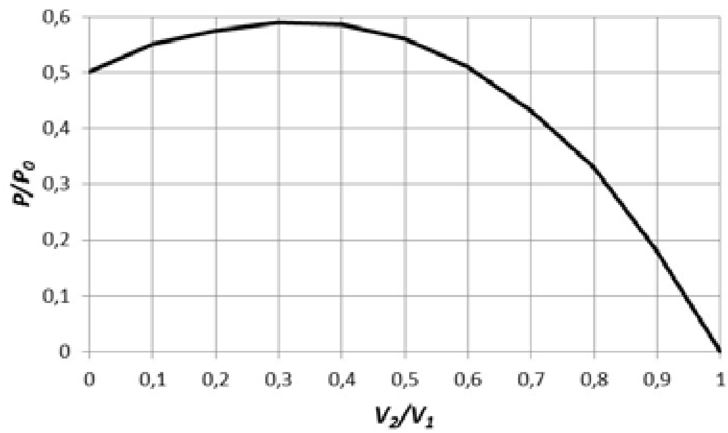


Fig. 3.16. Graphical expression of the Betz limit (Source: Ghosh & Prelas, 2011)

In Fig. 3.16:
V_1 – wind speed before passing of wind through turbine rotor (m/s);
V_2 – wind speed after passing of wind through turbine rotor (m/s);
P – wind power before passing of wind through turbine rotor (W);
P_0 – wind power after passing of wind through turbine rotor (W).

The Betz limit shows the possible power factor of an ideal rotor of a wind turbine. The power factor of real wind turbines is always lower than the ideal Betz limit.

3.3.3. Calculation of wind turbine energy production

Wind turbines are mostly classified by their rated power at a rated wind speed. Yearly energy output is a very important measure for evaluating a wind turbine. The payout time for the wind turbine will depend on its energy production. To calculate the expected energy output, the capacity factor of the turbine should be evaluated. The real wind turbine capacity factor will be from 0.20 to 0.30. A very effective enormous power wind turbine capacity factor could be 0.40. Energy produced from the wind turbine can be calculated using a simple equation:

$$E = C_P \cdot P \cdot t, \tag{3.10}$$

where:
E – energy (kWh) ;
C_P – power factor (–);
P – power (kW);
t – time (h).

An example of wind turbine energy production calculation:

By multiplying the rated power output by the capacity factor and the number of hours per year (8760 h/year), we can calculate an estimate of annual energy production for 100 kW. If the turbine produces 28 kW at the average wind speed of 6.7 m/s, the energy production per year will be: 100 kW · 0.28 · 8760 = 245,280 kWh.

3.3.4. Influence of land surface type on wind characteristics

The simple equation may be used to calculate the impact of the ground surface roughness on the speed of the wind:

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}, \tag{3.11}$$

where:
v – the wind speed at height H (m/s);
v_0 – the wind speed at height H_0 (could be taken from a wind atlas) (m/s);
α – land surface friction factor (–).

The friction factor α depends on the landform where the wind blows. Some values of the friction factor α are stated below:
- smooth hard ground, calm water – 0.10;
- tall grass on level ground – 0.15;
- high crops, hedges and shrubs – 0.20;
- wooded countryside, many trees – 0.25;
- small towns with trees and gardens – 0.30;
- large city with tall buildings – 0.40.

An example of influence of land surface type on the evaluation of wind characteristics:

According to the wind atlas, an area with crops, hedges and shrubs determinates a 5 m/s wind speed at a height of 10 m above the ground. The velocity and power of the wind at a height of 70 m should be calculated. The environmental conditions: temperature of +15°C and pressure of one atmosphere should be taken into consideration. From the above data, the friction coefficient α for the area with crops, hedges and shrubs, *equals* 0.20. At the temperature of 15°C and the pressure of 1 atmosphere, the air density equals $\rho=1.225\ kg/m^3$. Using the above-mentioned Eq. (3.11), the wind speed at a height of 70 m above the ground equals:

$$v_{70} = 5 \times \left(\frac{70}{10}\right)^{0.2} = 7.4\frac{m}{s}$$

and the wind power will amount to:

$$p_{70} = \frac{1}{2}\cdot\rho\cdot v^3 = 0.5\times1.225\times7.4^3 = 248.2\frac{W}{m^2}$$

It was calculated that at 70 m above the ground, the wind power is more than three times bigger than at the height of 10 m ($76.5\ W/m^2$).

3.4. Construction and types of wind turbines

Wind energy is a renewable or alternative energy source in relation to conventional energy sources. Apart from the energy expenditure related to the construction of such a power plant, generation of wind energy does not entail the burning of any fuel. In 2016, the global wind power capacity expanded to 486.749 MW (GWEC, 2017). Wind power is already the global leader in green technologies and its usage is constantly growing. A wind power plant is a plant that generates electricity using wind generators. Its main element is a wind turbine or wind rotor converting the kinetic energy of the wind into mechanical work in the form of rotational motion of the rotor. The main elements of a typical wind turbine are (Fig. 3.17): a rotor with blades, main shaft, gearbox, brake, coupling, generator, wind vane/anemometer, housing, tower, and yaw motor/gear.

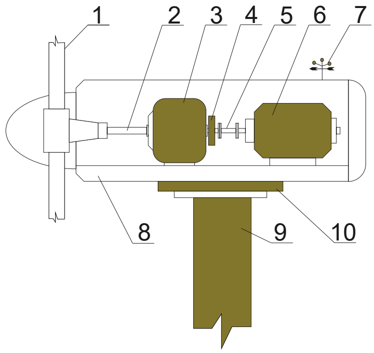


Fig. 3.17. Components of a wind turbine: 1 – rotor with blades, 2 – main shaft, 3 – gearbox, 4 – brake, 5 – coupling, 6 – generator, 7 – wind vane/anemometer, 8 – housing, 9 – tower, 10 – yaw motor/gear (Source: own elaboration)

The tower supports the rotor of the wind turbine at the desired height. The main types of towers used in wind turbines are the tubular steel tower, lattice tower, and the guyed tower. Examples of a tubular concrete tower, tubular steel tower, combined lattice tower and guyed tower are shown in Fig. 3.18A, B and C respectively. In large wind power plants, the towers have service shafts and controls for the operation of the plant. An example of the interior of a tubular steel tower is shown in Fig. 3.19.

A B C

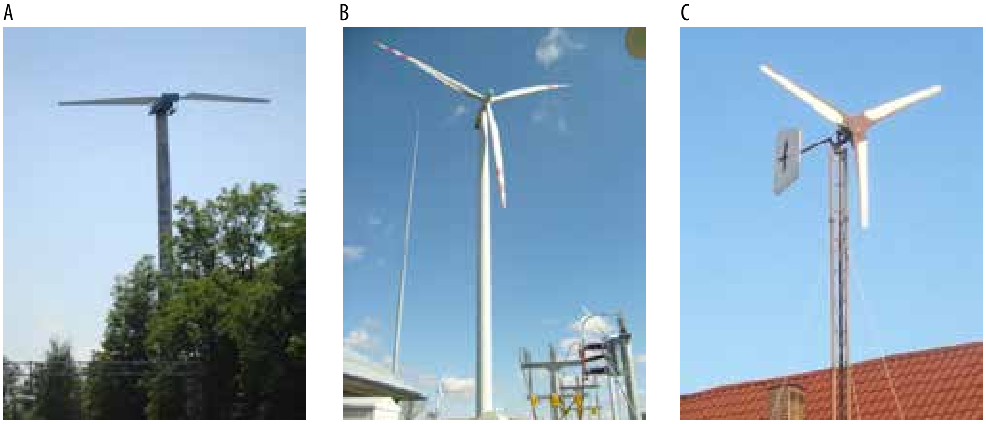


Fig. 3.18. Different types of towers: A) tubular concrete tower, B) tubular steel tower, C) combined lattice and guyed tower (Source: photo by T. J. Teleszewski)

As the central element of the drive system, the gearbox converts the low speed of the rotor shaft into a high rotation that drives the generator. The speed of a typical wind turbine rotor can be about 40 rpm, while the optimum speed of the generator can be about 1200 rpm (Mathew, 2006). A view of a sample gearbox made by the Winergy company is shown in Fig. 3.20.

A

B

Fig. 3.19. The interior of a tubular steel tower A) service ladder, B) control cabinet (Source: photos by T.J. Teleszewski)

Fig. 3.20. View of the gearbox in a wind turbine gondola (Source: photo by T.J. Teleszewski)

A reliable connection of the gearbox to the generator is an important factor in the successful production of wind energy. The coupling not only transmits the torque, but also protects the connected components from overloads and travelling leakage currents. An example of a shielded coupling that connects the gear drive to the generator is shown in Fig. 3.21.

Fig. 3.21. A wind turbine coupling (Source: photo by T.J. Teleszewski)

The generator is one of the most important elements in the conversion of wind energy to electricity. Due to the variable wind velocity, wind turbine generators work at variable power. Various types of generators are used. In small wind farms, direct current (DC) power generators are usually installed. Larger wind farms use single-phase or three-phase alternating current (AC) generators. Large wind power plants are usually integrated with power grids, and therefore three-phase alternating current generators are used. The generators used can be induction generators (asynchronous) or synchronous generators.

Wind turbines work according to a power curve (Fig. 3.22). The efficiency of a given wind turbine generator can be linked to a few points in the wind velocity scale: "cut-in speed" is the minimum wind velocity at which the machine will provide useful power, "rated wind speed" is wind velocity at which the wind turbine will generate its designated rated power and "cut-out speed" is the maximum wind velocity at which the turbine can supply energy. In order to control the power of wind turbines, the following methods are used: pitch control, stall control, active stall control and yaw control, which are described in many titles in the literature (Bianchi et al., 2007; Burton et al., 2011).

The main classifications of wind turbines can be identified depending on the axis alignment of the rotor, whether these are wind turbines with a horizontal axis of rotation, or horizontal axis machines, or turbines with a vertical axis of rotation, or vertical axis machines.

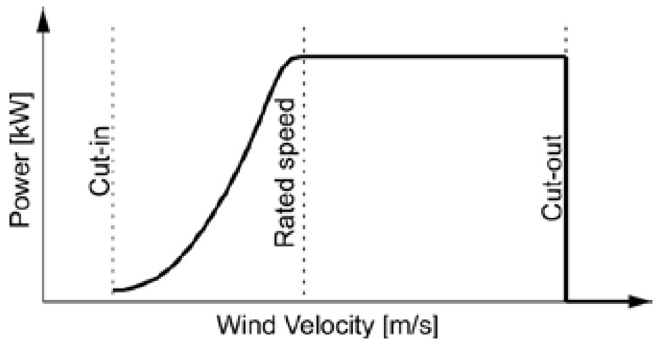


Fig. 3.22. Typical wind turbine power curve (Source: own elaboration)

Fig. 3.23. Types of vertical axis wind rotors: A) Savonius rotor, B) Spiral rotor, C) C-rotor type, D) rotor Darrieus H, E) combined Savonius and Darrieus rotors (Source: photos by T.J. Teleszewski)

Depending on the number of blades, wind turbines can be divided into: single-bladed, two-bladed (Fig. 3.18A), three-bladed (Figs. 3.18B-C), and multi-bladed. Three-bladed wind turbines are the most widespread for generating electric power, while the least widespread are the single-bladed ones. The main advantage of single bladed turbines is their low production costs, while the disadvantage is problems in correct balancing. Multi-bladed wind turbines are characterized by high aerodynamic resistance and high torque, which is why they are most often used as pump-driving devices.

The main advantage of vertical wind farms is that they work regardless of the direction of winds, which is why they can be used on areas with high roughness. Power plants with a vertical axis of rotation are characterized by different shapes of rotors. Individual types of rotors usually owe their names to the names of their creators. Figs. 3.23.A-E presents examples of vertical rotor types: Savonius rotor, Spiral rotor, C-rotor type, rotor Darrieus H, combined Savonius and Darrieus rotors, respectively.

3.5. A simplified design method of wind turbines

3.5.1. Basic quantities for the wind turbine design

The basic quantities necessary for the design of wind rotors are related to the wind energy conversion and aerodynamics of wind turbines. Theories on wind energy are extensively described in specialist literature (Mathew, 2006; Manwell et al., 2011; Ahmed, 2011). The main values related to wind energy are the power coefficient, Eq. (3.12), and the torque coefficient, Eq. (3.13) (Fig. 3.24):

$$C_P = \frac{2P}{\rho A u_W^3}, \tag{3.12}$$

$$C_T = \frac{2T}{\rho A u_W^2 R}, \tag{3.13}$$

where:

P – power developed by the turbine (W),
T – actual torque developed by the rotor (Nm),
A – area of the rotor (m^2),
u_W – wind velocity (m/s),
R – radius of the rotor (m),
ρ – density of air (kg/m^3).

The ratio between the velocity of the rotor tip and the wind velocity is defined as (Equ. (3.14-3.15)):

$$\lambda = \frac{R\omega}{u_W}, \tag{3.14}$$

or

$$\lambda = \frac{C_P}{C_T}, \tag{3.15}$$

where:

ω – angular velocity of the rotor (1/s).

The design tip speed ratio λ_d depends on the number *B* of rotor blades. Based on data from the literature (Mathew, 2006), λ_d can be described by the following approximation formula (3.16):

$$\lambda_d(k) = 0.63 + \frac{11.23}{B}, \tag{3.16}$$

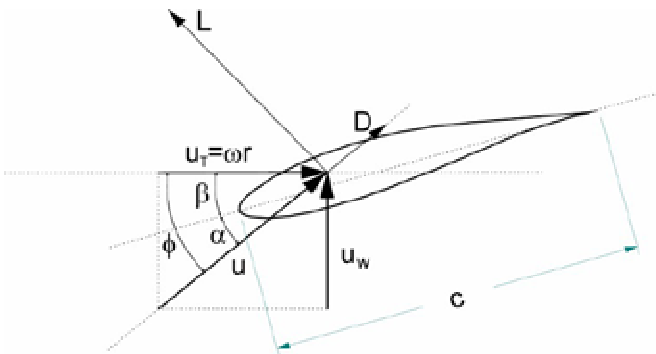


Fig. 3.24. Section of a rotating blade (Source: own elaboration)

Dimensional coefficients of lift and drag are described by the following relationships (Fig. 3.24), Equs. (3.17-18):

$$C_L = \frac{2L}{\rho A u_W^2}, \tag{3.17}$$

$$C_D = \frac{2D}{\rho A u_W^2}. \tag{3.18}$$

The basic parameters necessary to design the rotor are related to the rotor and the profile of the rotor blade. The parameters related to the rotor are the radius *R* of the rotor, the design tip speed ratio λ_d and the number of blades B. The sizes associated with the rotor blade profile are the design lift coefficient C_L and angle of attack α.

The projected radius of the rotor R can be determined from the dependence of Eq. (3.19) after taking into account the overall system efficiency η, and the design power coefficient C_{PD}:

$$R = \sqrt{\frac{2P_D}{C_{PD}\eta\,\rho\pi u_D^3}}\,, \tag{3.19}$$

where:

P_D – power expected from the turbine (W)

In order to determine a local tip speed ratio λ_r, blade setting angle β, and the length chord C (Fig. 3.24) in different cross-sections of the blade r, the following dependencies (Jansen et al., 1982) are used (Equs. (3.20-3.23)):

$$\lambda_r = \lambda_d \frac{r}{R}\,, \tag{3.20}$$

$$\phi = \frac{2}{3}\arctan\left(\frac{1}{\lambda_r}\right), \tag{3.21}$$

$$\beta = \phi - \alpha\,, \tag{3.22}$$

$$C = \frac{8\pi r}{BC_L}\left(1-\cos\phi\right). \tag{3.23}$$

When designing a rotor blade, the appropriate aerodynamic profile should be selected along with the angle of attack so as to minimize the drag force, and maximize the lift force, i.e. the ratio C_D/C_L should be as small as possible. In order to choose the shape of the airfoil for the rotor blade, one can use the available databases of various research institutes, eg: National Advisory Committee for Aeronautics (NACA), University of Illinois at Urbana-Champaign (UIUC) Airfoil Data Site, National Wind Technology Center's (NWTC) Information Portal, National Renewable Energy Laboratory (NREL).

3.5.2. An example of a preliminary design of a rotor with a horizontal axis

The following is an example of a rotor project for a small wind turbine with constant lift coefficient. Three rotor blades were adopted, for which the design tip speed ratio was determined according to Eq. (3.16):

$$\lambda_d(3) = 0.63 + \frac{11.23}{3} = 4.37 \tag{3.24}$$

The radius of the rotor was determined according to Eq. (3.25):

$$R = \sqrt{\frac{2P_D}{C_{PD}\eta\rho\pi u_D^3}} = \sqrt{\frac{2\cdot 300}{0.4\cdot 0.9\cdot 1.22\cdot \pi\cdot 8^3}} = 0.92\text{m} \tag{3.25}$$

The NACA 63_2-415 profile was chosen for the designed rotor, whose lift coefficient is 0.95 for a 5-degree approach angle of attack. Fig. 3.25 shows the aerodynamic characteristics of the NACA 63_2-415 profile (Abbott et al., 1945). Assuming the above angle of attack, the ratio between the drag coefficient and the lift coefficient is minimal and it is C_D/C_L=0.01. Table 3.1 presents a summary of the adopted design parameters of the rotor.

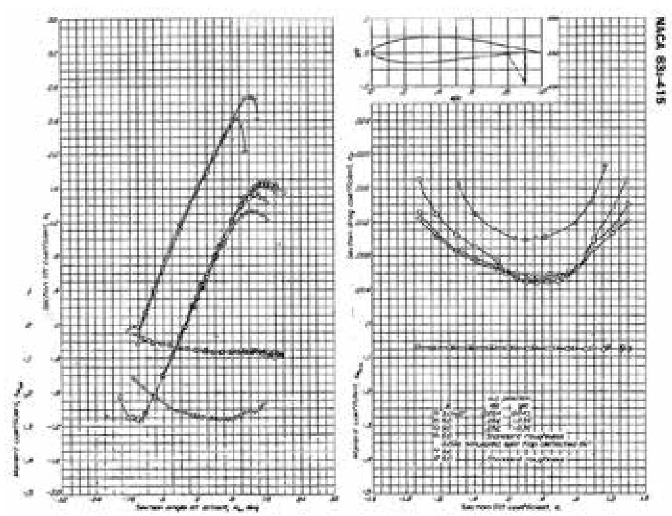


Fig. 3.25. Aerodynamic characteristics of the NACA 632-415 airfoil section (Source: Abbott et al., 1945)

Table 3.1. Assumed turbine design parameters with a constant lift coefficient (Source: own elaboration)

number of rotor blades B (–)	3
design tip speed ratio λ_d (–)	4.37
radius of the rotor R (m)	0.92
design lift coefficient C_{LD} (–)	0.95
corresponding angle of attack a_d (°)	5
design wind velocity u_D (m/s)	8

The results of chord $C(r)$ and setting angle for a blade rotor with a constant lift coefficient calculated using Eqs (3.20)-(3.23) are presented in Table 3.2.

Table 3.2. Calculation of chord and setting angle for a three-bladed rotor with a constant lift coefficient (Source: own elaboration)

Position	r	λ_r	ϕ	β	C
–	m	–	degrees	degrees	M
1	0.05	0.24	51.1	46.1	0.16
2	0.10	0.47	43.1	38.1	0.24
3	0.15	0.71	36.4	31.4	0.26
4	0.20	0.95	31.0	26.0	0.25
5	0.25	1.19	26.8	21.8	0.24
6	0.30	1.42	23.4	18.4	0.22
7	0.35	1.66	20.7	15.7	0.20
8	0.40	1.90	18.5	13.5	0.18
9	0.45	2.14	16.7	11.7	0.17
10	0.50	2.37	15.2	10.2	0.15
11	0.55	2.61	14.0	9.0	0.14
12	0.60	2.85	12.9	7.9	0.13
13	0.65	3.08	12.0	7.0	0.12
14	0.70	3.32	11.2	6.2	0.12
15	0.75	3.56	10.5	5.5	0.11
16	0.80	3.80	9.8	4.8	0.10
17	0.85	4.03	9.3	4.3	0.10
18	0.90	4.27	8.8	3.8	0.09
19	0.92	4.37	8.6	3.6	0.09

Another way of designing the rotor is to determine the lift coefficient, angle of attack and setting angle for the constant chord blade. The lift coefficient is determined from Eq. (3.23):

$$C_L = \frac{8\pi r}{BC}\left(1 - \cos\phi\right), \tag{3.26}$$

Table 3.3 presents a specification of turbine design parameters for the constant chord blade. Angles of attack were read from the characteristics of the selected profile (Fig. 3.25). The results of lift coefficient, angle of attack and setting angle for the constant chord blade of a three-bladed rotor are presented in Table 3.3.

Table 3.3. Assumed turbine design parameters for the constant chord blade (Source: own elaboration)

number of rotor blades *B* (–)	3
design tip speed ratio λ_d (–)	4.37
radius of the rotor *R* (m)	0.92
chord blade *C* (m)	0.2

Table 3.4. Calculation of setting angle, angle of attack and lift coefficient for a three-bladed rotor with a constant chord blade (Source: own elaboration)

Position	r	λ_r	ϕ	C	C_L	α	β
–	m	–	degrees	m	–	degrees	degrees
1	0.05	0.24	51.1	0.2	0.78	3.0	48.1
2	0.10	0.48	43.1	0.2	1.13	6.0	37.1
3	0.15	0.71	36.3	0.2	1.22	7.0	29.3
4	0.20	0.95	31.0	0.2	1.19	6.9	24.1
5	0.25	1.19	26.7	0.2	1.12	6.0	20.7
6	0.30	1.43	23.4	0.2	1.03	5.0	18.4
7	0.35	1.66	20.7	0.2	0.94	4.9	15.8
8	0.40	1.90	18.5	0.2	0.87	4.0	14.5
9	0.45	2.14	16.7	0.2	0.80	3.1	13.6
10	0.50	2.38	15.2	0.2	0.73	2.0	13.2
11	0.55	2.61	14.0	0.2	0.68	1.9	12.1
12	0.60	2.85	12.9	0.2	0.63	1.8	11.1
13	0.65	3.09	12.0	0.2	0.59	1.5	10.5
14	0.70	3.33	11.2	0.2	0.55	1.0	10.2
15	0.75	3.57	10.4	0.2	0.52	0.9	9.5
16	0.80	3.80	9.8	0.2	0.49	0.7	9.1
17	0.85	4.04	9.3	0.2	0.46	0.5	8.8
18	0.92	4.37	8.6	0.2	0.43	0.0	8.6

3.6. Location of wind farms

Wind velocity has the most important impact on wind farm efficiency, which depends primarily on the location of the wind power plant in the area (Mathew, 2016). All kinds of terrain obstacles in the form of buildings or trees affect the roughness of the terrain. This translates into a significant reduction in wind velocity and increased turbulence. According to the classification of terrain roughness (Şen, 1999), wind farms should be located in a large, open space, i.e. in cultivated areas or on the open sea (Şen, 1999; Tian et al., 2015). Given the considerable roughness of urban areas, they are not a favourable location for wind farms, especially wind turbines with a horizontal axis, which should be located on the dominant wind directions.

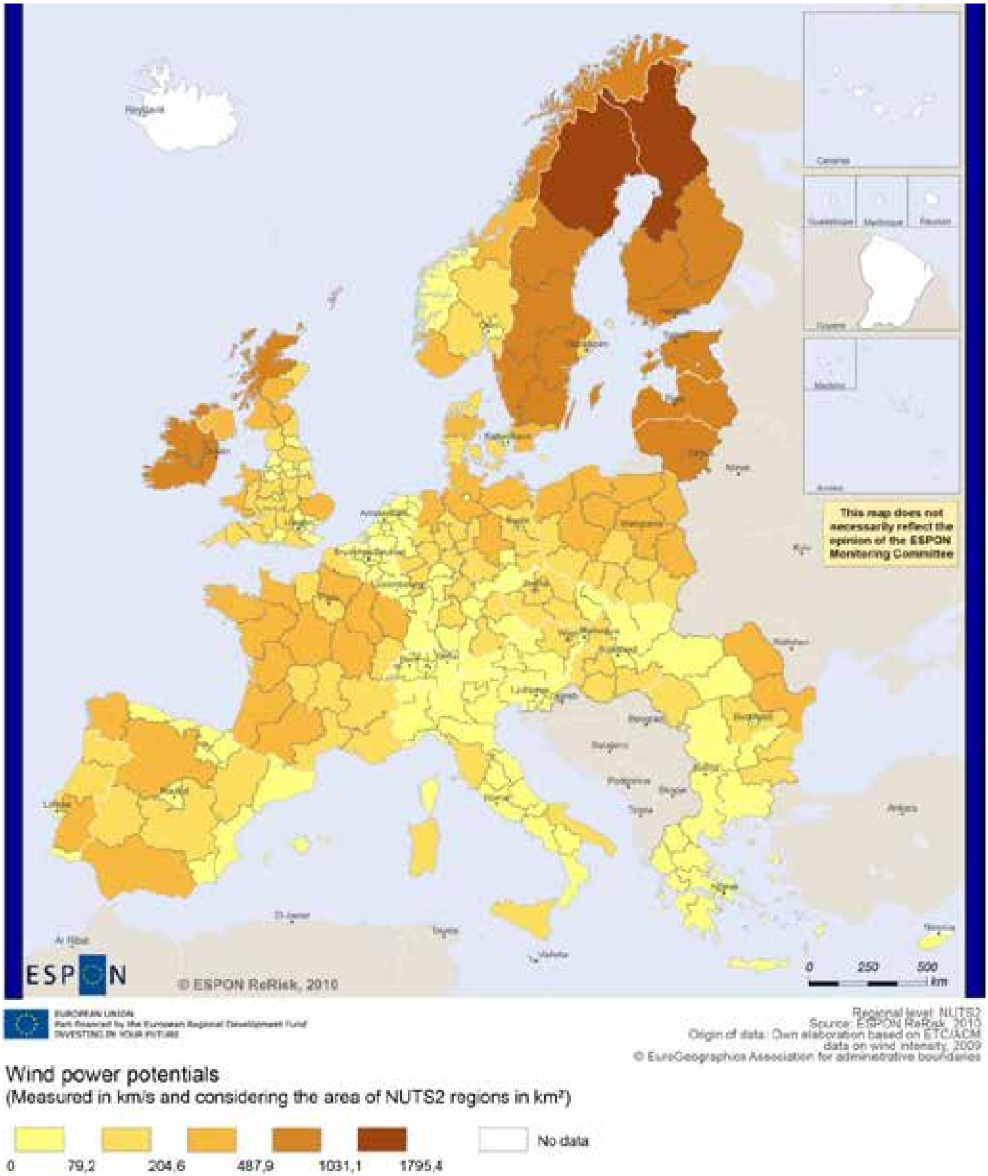


Fig. 3.26. Wind power potentials in Europe (Source: Velte et al., 2010)

An important parameter that affects the efficiency of wind farms is the height of the wind farm location above the ground level (Mathew, 2016). As the altitude above ground level increases, the wind velocity increases, which enhances the efficiency of the wind turbine. In cities with tall buildings, it is possible to use roofs to locate wind farms. Despite the fact that urban areas are characterized by high roughness of the area, which has a negative impact on the wind velocity, it should be borne in mind that the roofs of high buildings allow a higher wind velocity. Also, with proper arrangement of buildings, one can use the so-called Venturi effect (Dunlap, 2006; Blocken et al., 2008), which manifests itself in the increase of air velocity at the expense of static pressure. It should be noted here that vertical rotors can be used in urban areas, because their operation is independent of the direction of the wind (Sorko & Teleszewski, 2014a, 2014b, 2014c). Wind turbines with a horizontal axis of rotation also require accurate analysis of the wind direction. Small power plants or small wind turbines in a diffuser can be used in urbanized areas, which can generate electricity at low wind velocities, of around 5 m/s (Svorcan et al., 2013; Saravana-Kannan et al., 2013; WEB-1). It should be noted that the majority of small vertical power plants have a nominal velocity of 9-12m/s, less often 5-6m/s. In the catalogues of small wind farms, there is also the so-called start velocity at which the rotor starts to rotate. Most often this is about 2m/s. However, in practice, this velocity has no impact on the efficiency of wind farms.

Globally, some countries have good wind conditions which can be used to generate electricity using wind farms. Fig. 3.26 presents wind power potentials in Europe (Velte et al., 2010). The best wind conditions are found in northern countries such as Sweden, Finland, Ireland, Scotland, Northern Norway, Estonia, Latvia and Lithuania.

3.6.1. Wind measurements in wind energy

Wind measurement is designed to provide information about wind velocity and directions. Correctly carried out measurement of wind direction and velocity for wind energy needs should be made on a mast not lower than 75% of the height of the turbine rotor axis to which the wind farm is designed. Fig. 3.27 shows typical anemometers for wind velocity measurement: a cup anemometer with vanes to measure wind direction (A) and a sonic anemometer (B).

In the measurements to determine the wind energy capacity, 10-minute-long average results were taken as a standard. The results of such measurements are data sequences: date, hour, and 10-minute averages for wind velocity and directions, as well as humidity, temperature and air pressure. The distribution of the frequency of occurrence of a given wind velocity can be presented graphically in the form of a histogram. The frequency distribution of a given wind velocity was determined by summing the number of ten-minute measurements of wind velocity in a given velocity range $<u_i, u_{i+1})$.

$$T_i = \frac{n_i}{N} 100\% \tag{3.27}$$

where:
n_i – number of measurements from a given interval $<u_i, u_{i+1})$ (–),
N – number of all measurements in a given period (–).

A B

Fig. 3.27. Typical anemometers for measuring wind velocity: A) cup anemometer with vanes to measure wind direction, B) sonic anemometer (Source: photos by T.J. Teleszewski)

Fig. 3.29 presents an example of a wind velocity histogram on the building of the Faculty of Civil and Environmental Engineering of Bialystok University of Technology for measurements made in 2016. Localization of the measuring point is shown in Fig 3.28. The highest probability density is characterized by winds with a velocity equal to 1 m/s, which is a result that is insufficient to efficiently operate a wind turbine. The wind velocity histogram is interpolated using analytical functions. The probability density function f(u) of the wind velocity distribution is best reflected by the Weibull function (Equ. (3.28)):

$$f(u) = \frac{h}{c}\left(\frac{u}{c}\right)^{h-1} e^{-(u/c)^h} 100\% \tag{3.28}$$

where:
u – wind velocity (m/s),

h – Weibull shape factor (m/s),
c – scale factor (m/s).

Fig. 3.28. Location of the measuring point on the roof of the building of the Faculty of Civil Engineering and Environmental Engineering at Bialystok University of Technology (Source: WEB-2)

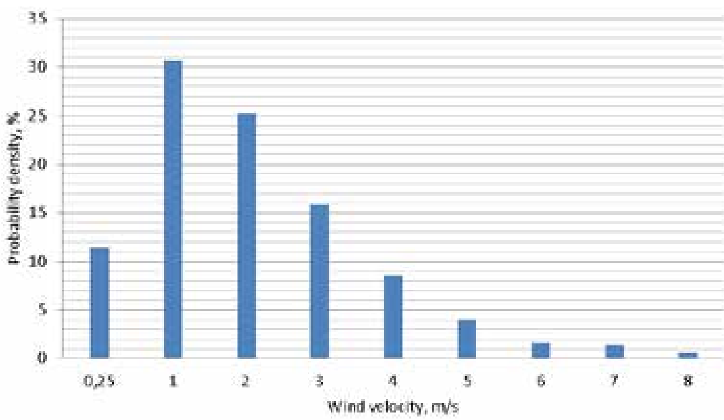


Fig. 3.29. Wind velocity histogram (Source: own eleboration)

The probability density functions of a wind regime are shown in Fig. 3.30. The Weibull shape factor and scale factor values for this case are 1.6 and 2.5 m/s respectively.

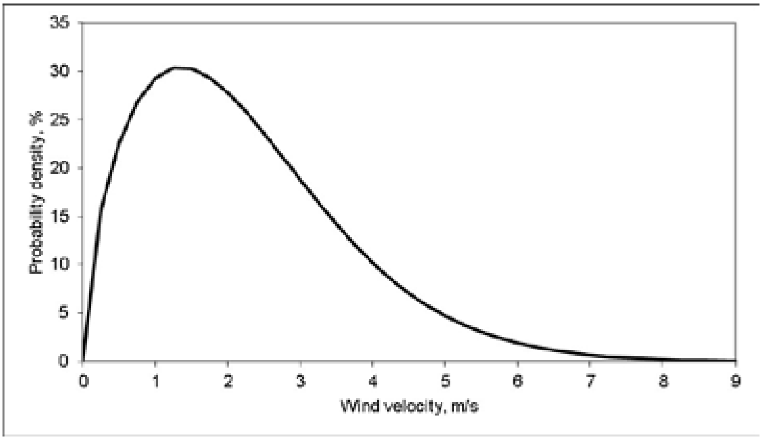


Fig. 3.30. Weibull probability density function (Source: own elaboration)

The wind average velocity u_m is determined according to the following relationship Equ. (3.29-3.30):

$$u_m = \frac{\sum_{i=1}^{N} u_i n_i}{N} \tag{3.29}$$

or

$$u_m = \int_0^{\infty} u \cdot f(u)du \tag{3.30}$$

For the above histogram, the average velocity is 2.11 m/s.

References

Abbott, I. H., Doenhoff, A. E., & Stivers, L. S. (1945) *Summary of Airfoil Data*. National Advisory Committee for Aeronautics. Report number: 824.

Ahmed, S. (2011) *Wind Energy: Theory and Practice*. 2nd Edition. PHI Learning Pvt. Ltd.

Bianchi, F. D., Battista, H. & Mantz, R. J. (2007) *Wind Turbine Control Systems. Principles, Modelling and Gain Scheduling Design*. Advances in Industrial Control. Springer.

Blocken, B., Moonen, P., Stathopoulos, T. & Carmeliet, J. (2008) Numerical Study on the Existence of the Venturi Effect in Passages between Perpendicular Buildings. *Journal of Engineering Mechanics*, 134(12), 1021-1028.

Burton, T., Jenkins, N., Sharpe, D. & Bossanyi, E. (2011) *Wind Energy Handbook*. 2nd Edition. Wiley.

Dunlap, D. W. (2006) At New Trade Center, Seeking Lively (but Secure) Streets. *The New York Times*. [Online] 7th December, B4. Available from: https://www.nytimes.com/2006/12/07/nyregion/07blocks.html [Accessed 10th August 2018].

EEA (2009) *Europe's onshore and offshore wind energy potential. An assessment of environmental and economic constraints*. EEA Technical report. Report number: 6.

Ghosh, T. K. & Prelas, M. A. (2011) *Energy Resources and Systems. Volume 2: Renewable Resources*. Springer.

GWEC (2017) *Global Wind Statistics 2016*. Global Wind Energy Council.

Jansen, W. A. M., Smulders, P. J. & Lysen, E. H. (1982) Wind Rotor Design. *Renewable Energy Review Journal*, 4(1), 14-28.

Manwell, J. F., McGowan, J. G. & Rogers, A. L. (2010) *Wind Energy Explained: Theory, Design and Application*. 2nd Edition. Wiley.

Mathew, S. (2006) *Wind Energy. Fundamentals, Resource Analysis and Economics*. Springer.

Saravana-Kannan, T., Mutasher, S. A. & Kenny-Lau, Y.H. (2013) Design and flow velocity simulation of diffuser augmented wind turbine using CFD. *Journal of Engineering Science and Technology*, 8(4), 372-384.

Şen, Z. (1999) Terrain topography classification for wind energy generation. *Renewable Energy*, 16, 904-907.

Sorko, S. A. & Teleszewski, T. J. (2014a) Modelowanie parametrów aerodynamicznych urządzeń energetyki wiatrowej I. Aerodynamiczna analiza profili wirników turbin i rotorów wiatrowych. *Symulacja w Badaniach i Rozwoju*, 5(1), 43-55.

Sorko, S. A. & Teleszewski, T. J. (2014b) Modelowanie parametrów aerodynamicznych urządzeń energetyki wiatrowej II. Analiza aerodynamiczna turbin wiatrowych o poziomej osi obrotu. *Symulacja w Badaniach i Rozwoju*, 5(1), 57-69.

Sorko, S. A. & Teleszewski, T. J. (2014c) Modelowanie parametrów aerodynamicznych urządzeń energetyki wiatrowej III. Analiza aerodynamiczna rotorów wiatrowych o pionowej osi obrotu. *Symulacja w Badaniach i Rozwoju*, 5(2), 119-128.

Svorcan, J., Stupar, S., Komarov, D., Peković, O. & Kostić, I. (2013) Aerodynamic design and analysis of a small-scale vertical axis wind turbine. *Journal of Mechanical Science and Technology*, 27(8), 2367-2373.

Tian, W., Ozbay, A. & Hu, H. (2015) Terrain effects on characteristics of surface wind and wind turbine wakes. *Procedia Engineering*. [Online] 126, 542-548. Available from: https://doi.org/10.1016/j.proeng.2015.11.302 [Accessed 10th August 2018].

Velte, D., Magro, E. & Jiménez, I. (2010) *ReRisk. Regions at Risk of Energy Poverty*. ESPON 2013.

WEB-1: AENews (2009) *Small, low sp,eed wind turbine.* Alternative Energy. [Online] Available from: http://www.alternative-energy-news.info/small-low-speed-wind-turbine [Accessed 10th August 2018].

WEB-2: www.google.pl/maps [Accessed 10th August 2018].