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Stanisław Gumuła

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Kraków

Agnieszka Woźniak*

State College
Polytechnic Institute
Krosno

Selection of geometric parameters and motion parameters of a wind turbine

The choice of constructional parameters for a d turbine designed to use specific local resources of wind kinetic energy in order to reach the required level of energy production with possibly low capital expenditures is not an easy task. The present study displays how the chosen constructional parameters and the parameters of wind turbine work and the local resources of wind kinetic energy influence the amount of the produced energy. It also presents how it is possible to affect the amount of capital expenditures necessary to build a turbine by choosing these parameters. The most important parameters were taken into account in the performed analyses, among those parameters influencing the amount of the energy production and the value of economic indicators: the diameter of the turbine runner, the height of the runner axle over the ground level, rated power of the turbine, the value of rated speed of wind. The presented method of the comparative analysis enabling the choice of the parameters for the wind turbine designed to perform specific tasks is universal and can be applied for all types of wind turbines intended to use any local wind resources.

1 Introduction

The production of the given amount of electrical energy can be realized with the use of wind turbines which significantly differ in terms of geometrical parameters of runners and speed characteristics for the work of turbines. The power of the

*E-mail: wozniakaga@interia.pl

wind stream blowing towards the turbine blades is proportional to the second power of the diameter of the blade circle and the third power of the speed of the wind stream. However, the wind turbine power is not proportional to the power of the wind stream. The relation between these values may differ. It may be influenced by three wind speeds characteristic for a turbine: starting speed, speed of at which the turbine reaches the rated power (rated speed), limit velocity (speed of at which a turbinr turns off). The power of the turbine amounts to zero for the wind speed in the range between zero to the starting speed with the constant diameter of the blade circle. The turbine power is approximately proportional to the third power of the wind speed in the range from the starting speed to the rated speed. The turbine has a constant power in the range from the rated speed to the speed of turning off. The turbine has obviously zero power again while over the speed of turning off.

The other factor conditioning the possibilities of energy generation by the turbine, apart from the parameters characteristic for the turbine, are the local resources of wind kinetic energy. The year average wind speed completely characterises the local resources of wind energy. On the basis of the year average of wind speed and the characteristics based on Weibull's distribution it can be calculated how many hours in a year wind of a given speed will blow. According to Weibull's characteristics, the faster the wind is the shorter the time of energetically effective speed. In this situation the problem of the choice of the rated power of the turbine arises. Assuming too little rated power of the turbine, and consequently, the power of the generator cooperating with it, eliminates the possibility of the use of this part of the winf stream power, which is bigger than the rated power of the turbine. The assumption of too big rated power of the turbine results in the increase in the capital expenditures, which restricts its use to few small number of hours in a year. It means that the choice of the most effective value of the rated power of the turbine strictly depends on the local resources of wind energy which are fully characterised by the year average of wind speed. What is more, the project of the turbine has to take all the mentioned parameters into consideration and use them form the most effective configuration.

The presented thesis shows the example of a comparative analysis allowing the definition of the influence of the chosen parameters on the amount of the energy production and the economic investment indicators of the wind turbine. The presented way of performing the analysis is universal and can be applied to all types of turbines. The illustrations of the influence of the individual parameters on the energy production in the individual ranges of the turbine work were made with the use of the technical parameters of the 800 kW three-blade turbine produced by Enercon [6]. Three-blade turbines are the basic type of the turbines used in electrical power engineering. The power of the produced turbines of this type is several dozen between Watts to five megawatts. The further part of the performed analysis, aiming at the choice of the turbine for the given energy production, already includes this type of turbines of various powers. As a result of the performed analyses, the relations between the rated powers of this type of turbines, their geometrical parameters, the average wind speed and the amount of the produced energy were defined. Firstly, it was defined at which combinations of the construction parameters of the turbine and the resources of wind energy the given energy generation may be obtained. Moreover, it was defined how at the given value of energy production the choice of the constructional parameters and the parameters of the turbine work influences the amount of the investment in wind turbines and how is the produced energy devided among the individual ranges of the turbine work.

2 Influence of characteristic parameters of a wind turbine and wind energy resources on energy production

Designing a wind power plant (WPP) should be preceded with thorough measurement of wind resources in the place where it is to be installed. The initial evaluation of the conditions for the construction of a WPP in a given area is made on the basis of the map of year average wind speeds. The final estimation of the wind conditions should be made on the basis of the measurement results in the place (or places) where the investor is going to locate the wind power plant [1]. The analysis of the observation data should be made in the appropriately long continuous measurement series. The absolute minimum is a yearly series of measurements but not in all cases such short-term observation results would be representative. In the climate which is in Poland these changes may be significant. The theoretical resources of wind can change by several dozen percent between consecutive years [5]. Due to this fact the analysed results of the observation should be of many years. Figure 1 presents the variability of year average wind speed in three measurement points in Poland: Łeba (northern part), Warsaw (central part) and Nowy Sącz (southern part).

The wind conditions in Poland, especially in the south of the country are different from those which are in western Europe and the power plants produced there are not fitted well enough for the use in Polish conditions. For instance,

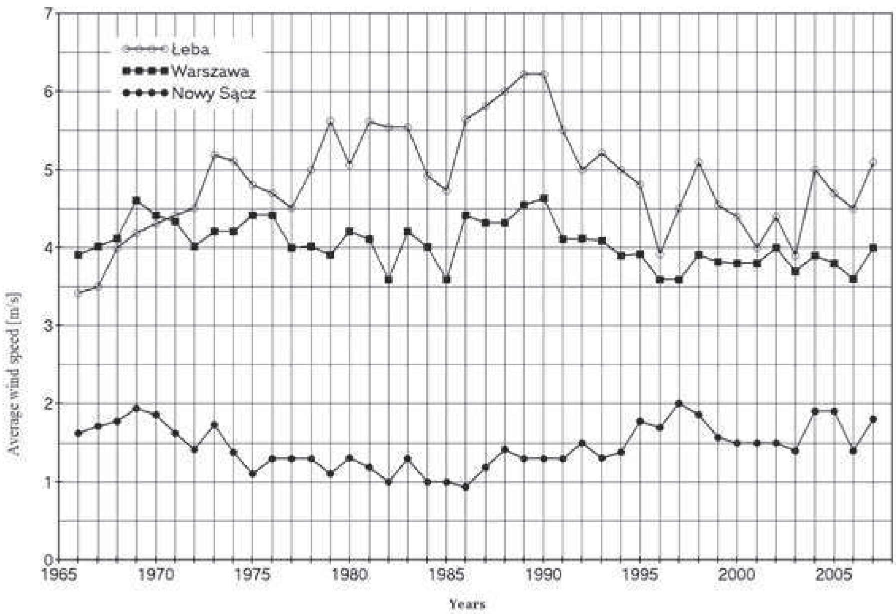

Figure 1. The many years variability of annual average wind speed for Łeba, Warsaw, Nowy Sącz from 1996 to 2007 (according to the data of IMGW Warsaw).

let's analyse a given wind turbine by Enercon's company E-48 three-blade, the technical data of which are included in Tab. 1.

Table 1. The geometric and motor parameters of the Enercon wind turbine E48/800 kW.

Rated power [kW]	Rotor diameter [m]	Tower height [m]	Rotational speed [rpm]	Cut-in wind speed [m/s]	Rated wind speed [m/s]	Cut-out wind speed [m/s]
800	45	50	16–30	2	14	28

Wind turbines have three regimes of operation: start-up, subrated and rated, corresponding to the velocity band between its cut-in wind speed (v_{cut-in}) and cut-out wind speed ($v_{cut-out}$). Usually the unitstarts supplying useful output power at the cut-in speed, showing increase in power produced with increase in wind speed up to the rated wind speed (v_r) of the turbine. The rated speed is the minimum wind speed at which the wind turbine generates its designated rated power, while the cut-out wind speed is a maximum wind speed at which the turbine switches off to prevent mechanical damage to the machine. At velocities between the rated wind speed and cut-off wind speed, the unit is designed to produce constantrated power when sufficient wind is available.

In fairly steady wind conditions, the annual amount of electric energy produced by the wind turbine can be characterized by the following two equations [2]:

$$E_1 = \frac{\gamma}{\beta} P_r T_r \int\limits_{v_{cut-in}}^{v_r} \left[\left(\frac{v}{\beta}\right)^{(\gamma-1)} e^{-\left(\frac{v}{\beta}\right)^{\gamma}} \right] N(v) dv \;\; \text{[kWh/year]} \tag{1}$$

in the case of subrated power regime, for the wind speed range from v_{cut-in} to v_r, and

$$E_2 = \frac{\gamma}{\beta} P_r T_r \int\limits_{V_r}^{v_{cut-out}} \left[\left(\frac{v}{\beta}\right)^{(\gamma-1)} e^{-\left(\frac{v}{\beta}\right)^{\gamma}} \right] dv \;\; \text{[kWh/year]} \tag{2}$$

in the case of rated power regime, for the wind speed range from v_r to $v_{cut-out}$, where γ and β are respectively the Weibull shape and scale parameters, P_r is the rated power, v is the speed of wind, and T_r denotes the time work of wind turbine in the individual ranges. The polynomial $N(v)$ describing dependence of power of the generator on the speed of the wind, the coefficients of the approximation function should be calculated, for example with the use of the least squares method. The total energy produced by the wind turbine in a year is the sum of contributions from each power regime

$$E_t = E_1 + E_2 \;\; \text{[kWh/year]} \,. \tag{3}$$

Using the producer's data [6] and taking the conditions under consideration, i.e. the cut-in and cut-out wind speed, and the rated wind speed as a computational speed, the probable amount of energy in a year can be calculated. Total annual energy production and its contributions from the Enercon's wind turbine E-48 versus average wind speed are presented in Fig. 2. If the wind turbine is situated in the place where the average yearly speed reaches 8 m/s, the amount of the energy produced in a year will be over nine times bigger than in the place with the wind conditions of 3 m/s.

The knowledge of wind properties and its characteristics has basic significance for evaluation of energetic resources of a given region, usefulness of the investment in construction of a wind power plant, choice of the most beneficial constructional solution. Figure 3 lists the values of the produced energy in a year depending on the computational speed of the wind power plant at the same average yearly speed $v_{sh} = 4$ m/s for various rated powers.

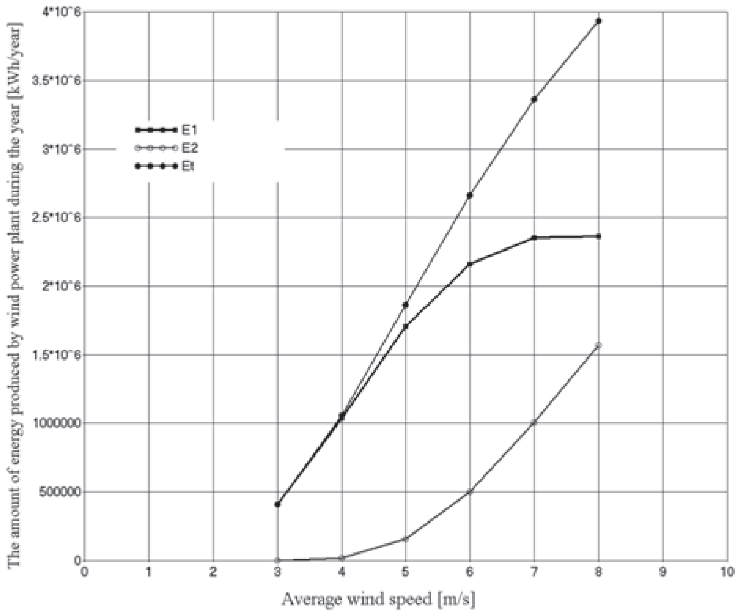

Figure 2. The dependence of the amount of electrical energy produced in a year by the Enercon's wind power plant on the average yearly wind speed.

3 Selection of geometrical and work parameters of a turbine in order to provide the given level of energy production

We consider the method of determining the optimal dimensions of a three-wing wind turbine with a horizontal axis of rotation and its motion parameters for the given wind conditions and the annual quantity of produced electricity. Assuming the yearly demand for electric energy and knowing the average yearly wind speed at 10 m over the ground level in the place of the foreseen localization of the wind power plant, the fundamental geometric dimensions of the wind turbine can be defined, i.e., the dimension of the rotor, height of the rotor axis over the ground level, as well as the motor parameters, i.e., the rotational speed of the rotor and the amount of electric energy produced during the year [2].

The method of the chooising the geometric and motor parameters of the wind power plant will be presented. The following parameters will be the starting point:

- yearly demand for electric energy E_t [kWh/year],

- average yearly wind speed v_{sh} [m/s],
- maximum circumferential speed of the end of the rotor blades which may be in the range from 60 to 100 m/s,
- foreseen technical efficiency period of the wind turbine.

3.1 Computational results

Table 2 presents the results for the demand $E_t = 50000$ kWh/year, assuming the average yearly wind speed $v_{sh} = 4$ m/s, the maximum speed of the end of the rotor blades 80 m/s and the foreseen time of the technical efficiency of the device 25 years. The considerations included the range of the rated speeds from 5 to 14 m/s.

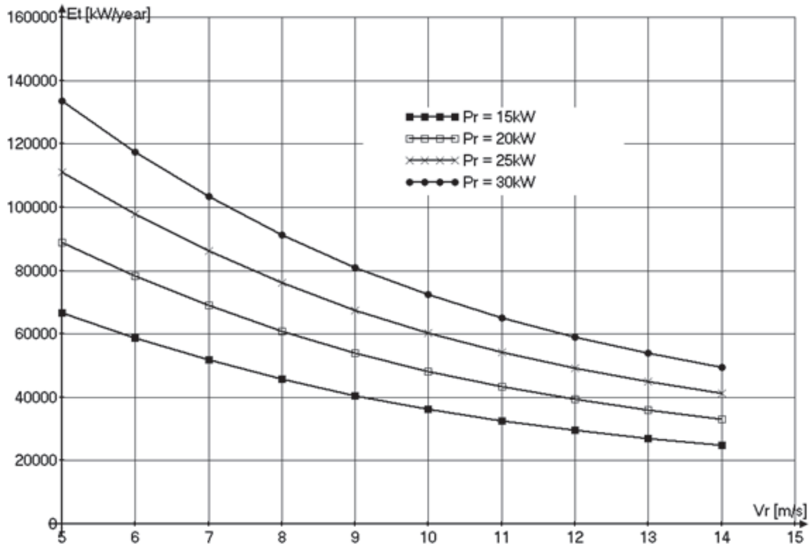

Figure 3. Total electric energy produced in a year as a function of the rated wind speed of the turbine for the same average annual wind speed ($v_{sh} = 4$ m/s).

The wind turbines which are able to produce the planned amount of electric energy were chosen for further analysis. The constructional parameters of these power plants are presented in Tab. 3.

As it can be seen (Tab. 3), the similar yearly amount of electric energy at the same wind conditions can be gained from wind turbines of various geometric dimensions.

Table 2. The amount of the produced energy for P_r=15, 20, 25, 30 kW.

Rated wind speed [m/s]	Annual energy production [kWh]			
	Rated power [kW]			
	15	20	25	30
5	66730	88980	111200	133500
6	58760	78350	97930	117500
7	51710	68940	86180	103400
8	45630	60850	76060	91270
9	40490	53980	67480	80980
10	36170	48230	60290	72350
11	32560	43400	54260	65110
12	29510	39350	49190	59020
13	26940	35920	44900	53890
14	24760	33010	41260	49520

Table 3. Wind turbine parameters (for $E_t \geq 50000$ kWh/year).

Rated power [kW]	Rated wind speed [m/s]	Rotor diameter [m]	Tower height [m]	Demand for electric energy (E_t) [kWh/year]
15	7	15.312	23.781	51710
20	9	12.128	20.915	53980
25	11	10.035	19.032	54260
30	13	8.556	17.700	53890

Assuming the presented constructional solutions of the individual components, the construction cost of the whole wind power plant should be estimated [4]. The mass and the costs of the purchase were estimated on the basis of the statistical data and cannot be the basis for the real estimation of the presented projects. It can be stated on the basis of the performed analysis that the fourth project (30 kW) is the most beneficial solution.

The amount of the produced energy in two regimes, i.e. in the rated range and the subrated range (Eqs. (1) and (2)) can be the second criterion of the wind turbine choice. We can conclude from Tab. 4 that the first project (15 kW) will be the most beneficial. The wind power energy from the this project, from among

Table 4. The list of the data to define the depreciation period for the chosen wind power plants.

Rated power [kW]	Demand for electric energy E_t [kWh/year]	The annual value of energy produced [PLN/year]	Weight of power [kg] (presented in relative terms)	Investment cost [PLN] (presented in relative terms)
15	51710	19961	135	146
20	53980	21200	113	118
25	54260	21189	100	100
30	53890	19030	84	86

the four presented variations, will produce most energy in the rated range (23% of the total produced energy). Till this moment we have been discussing the case when the power plants were in the same wind conditions, i.e., in the area with the same average yearly speed, in our case it was the speed $v_{sh} = 4$ m/s.

Table 5. Total energy produced within a year by the selected wind turbines with the division into two operating ranges.

P_r [kW]	E_t [kWh/year]	E_1 [kWh/year]	E_2 [kWh/year]
15	51710	39860	11850
20	53980	50700	3284
25	54260	53680	580
30	53890	53820	70

Let's consider the localization of the wind power plant in various wind conditions at the given power and the given rated speed. Let's consider a series of types of power plants with low powers $P_r = 15$, 20, 25 and 30 kW. The rated speeds which will be discuss are the following: $v_r = 8$, 9, 10 and 11 m/s.
The character of the curves presented in Fig. 2 is kept for other examined wind turbines with the powers of 20, 25 and 30 kW, and the percentage of energy E_1 and E_2 in the total amount of energy produced in a year by these four power plants is identical. The character of the curves presenting the diagram of total energy produced in a year for the power plant with various rated powers depending on the average yearly speed is depicted in Fig. 5. The used computational speed amounts here to 11 m/s. We can notice in Fig. 5 that if the demand for energy

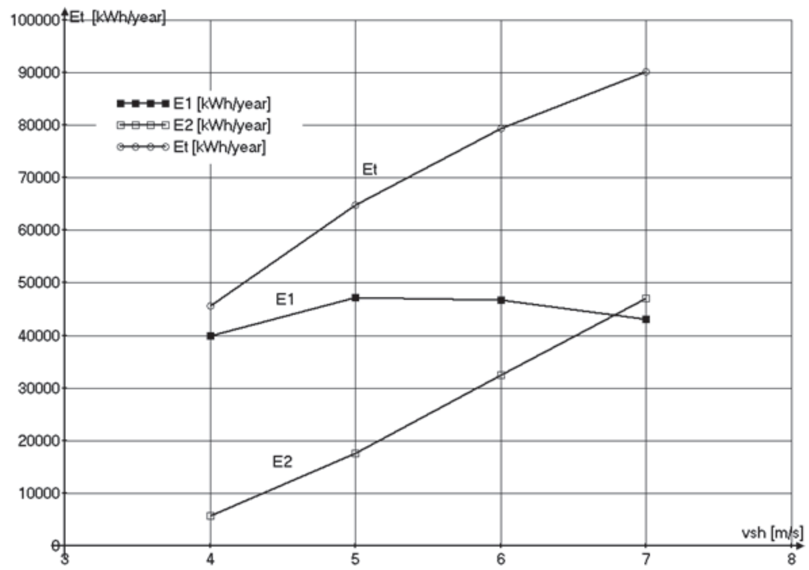

Figure 4. Energy produced in individual ranges: E_1 i E_2 for the power plant ($P_r = 15$ kW and $v_0 = 8$ m/s, $D = 12.5$ m, $H = 21$ m, $n = 122$ rpm).

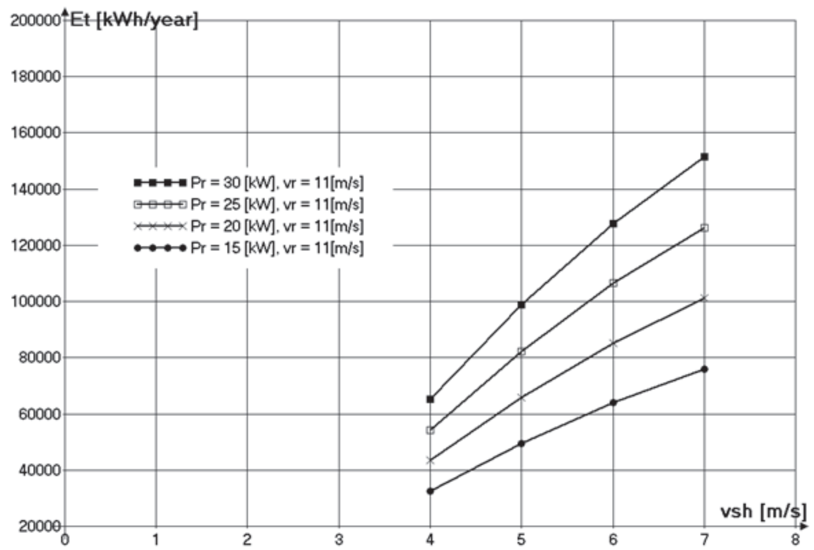

Figure 5. Energy produced in a year for the power plants with the powers $P_r = 15$, 20, 25, 30 kW for the computational speed $v_r = 11$ m/s.

Table 6. The parameters of the power plant ($P_r = 15$ kW, $v_r = 8$ m/s, the rotor diameter – $D = 12.5$ m, the tower height – $H = 21$ m, the rotational speed – $n = 122$ rpm).

v_{sh} [m/s]	E_1 [kWh/year]	E_2 [kWh/year]	E_t [kWh/year]
4	39960	5674	45634
5	47160	17600	64760
6	46820	32520	79340
7	43050	47110	90160

amounts to about 100000 kWh/year, such energy can be generated in the power plant of the power $P_r = 20$ kW but also in the power plant where $P_r = 30$ kW. However, the power plant $P_r = 30$ kW may be situated in the place of the average annual speed equaling 5 m/s, while the power plant with the rated power of 20 kW, in order to generate such energy, has to have the wind conditions for which the average yearly speed is 7 m/s.

4 Summary

The study depicts the method of defining the amount of energy produced by the wind turbine with respect to both the subrated range of the turbine work and the rated one. The relation between the year average wind speed in the place of the turbine localization, the rated power of the turbine and the amount of the produced energy was defined (Tab. 2). It was shown how the given amount of produced energy can be obtained by choosing the rated power of the turbine (the diameter of the runner, the height of the runner axle over the ground level) at different local year average speeds of wind (Tab. 3). It was presented how the choice of the constructional variant of the turbine for production of the given amount of energy influences the cost of the investment (Tab. 4). The results of the performed analyses describe the procedure enabling to define the geometrical parameters and the parameters of the wind turbine work that assure the given level of the energy production at the minimal investment costs [3].

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Wybór geometrycznych i ruchowych parametrów turbiny wiatrowej

S t r e s z c z e n i e

Dobór parametrów konstrukcyjnych oraz parametrów pracy turbiny wiatrowej do określonych lokalnych zasobów energii kinetycznej wiatru w celu osiągnięcia wymaganego poziomu produkcji energii przy możliwie niskich nakładach inwestycyjnych nie jest zadaniem łatwym. W przedstawionej pracy pokazano w jaki sposób wybrane parametry konstrukcyjne i parametry pracy turbiny wiatrowej oraz lokalne zasoby energii kinetycznej wiatru wpływają na wielkość produkowanej energii a następnie w jaki sposób można kształtować wielkość nakładów inwestycyjnych niezbędnych do wybudowania turbiny poprzez dobór tych parametrów. W przeprowadzonych analizach spośród parametrów mających wpływ na wielkość produkcji energii i na wartość wskaźników ekonomicznych uwzględniono te najważniejsze: średnicę wirnika turbiny, wysokość osi wirnika nad poziomem gruntu, moc nominalną turbiny, wartość prędkości nominalnej wiatru to znaczy prędkości wiatru przy której turbina osiąga moc nominalną. Przedstawiona metoda analizy porównawczej umożliwiająca dobór parametrów projektowanej turbiny wiatrowej do wykonania określonych zadań jest uniwersalna i może mieć zastosowanie do wszystkich typów turbin wiatrowych przewidzianych do pracy przy dowolnych lokalnych zasobach wiatru.