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A Research Towards Meeting the Electricity Demand of a Plant via Wind Turbine

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Abstract: In this study, the use of individual wind turbines towards meeting the electricity demands of a plant was emphasized. For this purpose, the electrical energy demand of the plant was revealed and then the mathematical equations directed towards determining whether the selected wind turbine could meet the electrical energy demand of the plant. The use of four types of wind turbines with different technical features for meeting the energy demands of three plants with different characteristics was evaluated in view of the mathematical equations established. The suitable wind turbines as well as the unsuitable ones were determined for every plant as a result of evaluations. This study was designed especially in a way that the plant which intends to take benefit of wind energy could pattern after. It is possible for the managements to determine the suitable wind turbines for themselves by putting their own data in the mathematical equations.

Key words: Wind, wind turbine, plants, electric requirement, power

INTRODUCTION

It is a fact that the limited reserves of fossil origined energy resources will be exploited in a near future. When the reserves of fossil fuels are examined based on the figures of 1996, it is estimated that the coal reserves will run out in 235 year, oil reserves in 43 years and natural gas reserves in 66 years. Moreover, the prices of these energy resources are increasing with the decreasing reserves. Today, the cost energy obtained from coal is 4.8-5.5 cent kW h^{-1}, while these values are 3.9-4.4 cent kW h^{-1}, 11.1-11.4 cent kW h^{-1} and 4.0-6.0 cent kW h^{-1} for gas origined energy, nuclear energy and wind energy, respectively (Acar, 2005). Adverse environmental affects of the energy sources other than wind cannot be ignored. Huge increments occurred in air pollution in recent years. In addition, there is an increasing demand for electric energy due to industrialisation and comfort.

Wind energy is one of the leading ones among the new, renewable, clean and cheap energy resources. This is an important resource of energy which has always been popular in recent years and which has exhibited a rapid technological development.

It is estimated that the world wind energy potential is 26.000 TW h yr^{-1} within the area between 50° north and 50° south latitudes and only 9.000 TW h yr^{-1} capacity is being used due to economical and other reasons. It is also reported that 27% of the world total terrestrial areas is under the effect of an average annual wind speed of higher than 5.1 m s^{-1}. It is calculated that an established power of 240.000 GW can be obtained with a production capacity of 8 MW km^{-2}, based on the assumption that it is possible to utilize this wind energy (Akgun and Dundar, 2005).

Northern European Countries are especially advanced in this respect. Established wind powers of Germany, Denmark, Netherlands and UK in the middle of the year 2000 are 6,096, 2,301, 433 and 362 MW, respectively, whereas the established wind power of Spain, a Mediterranean country in the mid-2000 is 2,481 MW. According to 1999 data, established wind powers of Portugal, Italy and Greece are 61, 277 and 158 MW, respectively (Klug, 2001). On the other hand, Turkey is on the last orders in the use of wind energy with an established power of 18.9 MW.

However, the survey studies show that Turkey has an important wind potential. Wind energy resources of Turkey are theoretically sufficient to meet the whole electricity demand of Turkey. Technical wind energy potential of Turkey is 83,000 MW and Turkey is the most promising country in Europe, regarding the wind potential (Uyar, 2005). Conversion of this potential into energy will increase the ratio of energy supplied from the local resources of Turkey. This ratio may reach important levels if the other renewable energy resources are included. It is even possible for Turkey to generate more energy than needed.

Wind energy can be converted into electrical energy by different means. These may include supporting the national network with wind centrals, or use of individual wind turbines in order to meet electric demand of the plants.

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In this study, meeting the electrical energy demand of plants via wind turbines was emphasized. For this purpose, the shortest mathematical equation related to whether the electrical energy demand of the plant can be met with a single wind turbine or not. Thereafter, three different plants were evaluated with four different types of wind turbine.

MATERIALS AND METHODS

Established power of plants: The established power of a plant is expressed as the sum of maximum consumption power and alternate power as can be seen in the following equation (Yavuzcan, 1994):

$$N = N_{max} + N_y \tag{1}$$

Maximum consumption power consists of the sum of three different factors (Yavuzcan, 1994):

$$N_{max} = N_a + N_k + N_{ka} \tag{2}$$

The alternate power in the Eq. 1 is in equation in the case of a defect in some of the centrals or an increase in the energy demands. Alternate power is calculated by the equation below (Yavuzcan, 1994):

$$N_y = r_k \cdot N_{max} - N_{max} = (r_k - 1) \cdot N_{max} \tag{3}$$

Here, r_k is the reserve coefficient, which is accepted as 1.2-1.3 for power stations. In some cases, r_k can be equal to or more than 2.

The following equation is obtained when the Eq. 2 and 3 are put in the Eq. 1:
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$$N = r_k \cdot (N_a + N_k + N_{ka}) \tag{4}$$

This equation is the last one which gives the established power of the plant.

Power that can be obtained from a wind turbine: Wind has a kinetic energy due to its speed. This kinetic energy is calculated with the following equation (Klug, 2001):

$$E = \frac{m}{2} \cdot v^2 \tag{5}$$

The following steps can be followed for establishing the power value of this kinetic energy:

First, the derivative of time dependent kinetic energy of power is obtained (Klug, 2001):

$$P = \frac{dE}{dT} \tag{6}$$

Mass of the air (m) in Eq. 5 is determined according to the following equation (Klug, 2001):

$$m = \rho \cdot v \cdot A \tag{7}$$

The following equation is obtained by putting the mass value (m) in Eq. 7, in the Eq. 5 (Klug, 2001):

$$E = \frac{\rho}{2} \cdot A \cdot v^3 \tag{8}$$

Equation 8 and 6 can expressed in combination as follows, when they are evaluated for unit time (Klug, 2001):

$$P = \frac{\rho}{2} \cdot A \cdot v^3 \tag{9}$$

This equation gives the total power of the wind. However, it is not possible to convert all the power of the wind to unable power. At this point, ideal power coefficient (Cp) of wind turbine rotors is put into use. Furthermore, a mechanical loss of the system is also in equation. This is expressed as the "mechanical efficiency (η)". Under these circumstances, Eq. 9 turns into the following form as the usable power equation of the wind turbine (Klug, 2001):

$$P = \frac{\rho}{2} \cdot A \cdot v^3 \cdot Cp \cdot \eta \tag{10}$$

The parameter ρ in this equation gives us the following equation when reduced to absolute temperature under 1 atm pressure and 0 °C (Vardar, 2002):

$$\rho = 1,293 \cdot \frac{273}{273 + t} \tag{11}$$

The cross-section area of wind turbine rotor (A):

$$A = \pi \cdot r^2 \tag{12}$$

Thus, the Eq. 13 is obtained when these two values are put in the Eq. 10:

$$P = \frac{176,4945 \cdot \pi \cdot r^2 \cdot v^3 \cdot Cp \cdot \eta}{273 + t} \tag{13}$$

Now, let's investigate the ideal power coefficient of the wind turbine: The equation is obtained when the rotor ideal power coefficient in the Eq. 13 is opened out (Ozdamar and Kavas, 1999):

$$Cp = Cp_{Schmitz} \cdot \eta_{profil} \cdot \eta_{tip} \quad (14)$$

The whirlpool losses here are calculated and shown in Table 1. On the other hand, the profile losses can be opened out as follows (Ozdamar and Kavas, 1999):

$$\eta_{profil} = 1 - \frac{\lambda}{\varepsilon} \quad (15)$$

Here, the slide number ϵ is stated with the equation (Dreese, 2000):

$$\varepsilon = \frac{C_L}{C_D} \quad (16)$$

Rotor tip speed ratio (λ) in the equation can be calculated with the following formula:

$$\lambda = \frac{\pi \cdot n \cdot r}{30 \cdot v} \quad (17)$$

The following equation can be used for calculating the tip losses (Ozdamar and Kavas, 1999):

$$\eta_{tip} = 1 - \frac{1.84}{B \cdot \lambda} \quad (18)$$

The equation below is obtained when the Eq. 15-18 are put into their places in the equation below:

$$Cp = Cp_{Schmitz} \cdot \left(1 - \frac{1.84 \cdot C_L \cdot v}{B \cdot \pi \cdot n \cdot r}\right) \quad (19)$$

When this equation is combined with the Eq. 13, the equation is obtained.

$$P = \frac{176.495 \cdot r \cdot v^3 \cdot \eta \cdot Cp_{Schmitz} \cdot (B \cdot \pi \cdot n \cdot r - 1.84 \cdot C_L \cdot v)}{B \cdot n \cdot (273 + t)} \quad (20)$$

When the opening of wind speed is realised, two wind speeds i.e. v and v' are in equation. v is the wind speed at the rotor hub height of wind turbine, while v' is the wind speed at a given height. v and v' values are calculated with the following equations (Klug, 2001):

$$v = \frac{u^*}{k} \cdot \ln \frac{h}{z_0} \quad (21)$$

$$v' = \frac{u^*}{k} \cdot \ln \frac{h'}{z_0} \quad (22)$$

When u* is drawn out of the Eq. 21, equation is obtained:

$$u^* = \frac{v' \cdot k}{\ln \frac{h'}{z_0}} \quad (23)$$

Putting this formula into the Eq. 20, the following is obtained.

$$v = \frac{\ln \frac{h}{z_0}}{\ln \frac{h'}{z_0}} \cdot v' \quad (24)$$

The following equation is obtained when the Eq. 23 is put into the Eq. 20:

$$P = \frac{176.495 \cdot r \cdot \left(\frac{\ln \frac{h}{z_0}}{\frac{h'}{z_0}} \cdot v'\right)^3 \cdot \eta \cdot Cp_{Schmitz} \cdot \left(B \cdot \pi \cdot n \cdot r - 1.84 \cdot C_L \cdot \left(\frac{\ln \frac{h}{z_0}}{\frac{h'}{z_0}} \cdot v'\right)\right)}{B \cdot n \cdot (273 + t)} \quad (25)$$

The useful power of wind turbine can be calculated with the aid of this equation and $Cp_{Schmitz}$ value in Table 1. Equation 17 is also used for determining the tip speed ratio λ which is required for obtaining $Cp_{Schmitz}$ value in Table 1.

The ratio of the wind turbine meeting the power demand of the plant: The meeting ratio of a single wind turbine the power demand of the plant can be calculated using the following equation:

$$MR = \frac{P}{N \cdot x} \quad (26)$$

When P values in the Eq. 25 are put into the Eq. 26, equation is obtained.

$$MR = \frac{176.495 \cdot r \cdot \left(\frac{\ln \frac{h}{z_0}}{\frac{h'}{z_0}} \cdot v' \right)^3 \cdot \eta \cdot Cp_{Schmitz} \cdot \left(B \cdot \pi \cdot n \cdot r - 1.84 \cdot C_L \cdot \left(\frac{\ln \frac{h}{z_0}}{\frac{h'}{z_0}} \cdot v' \right) \right)}{B \cdot n \cdot (273 + t) \cdot N \cdot x} \tag{27}$$

Consequently when the Eq. 27 and 4 are combined together, the Eq. 28 is obtained.

$$MR = \frac{176.495 \cdot r \cdot \left(\frac{\ln \frac{h}{z_0}}{\frac{h'}{z_0}} \cdot v' \right)^3 \cdot \eta \cdot Cp_{Schmitz} \cdot \left(B \cdot \pi \cdot n \cdot r - 1.84 \cdot C_L \cdot \left(\frac{\ln \frac{h}{z_0}}{\frac{h'}{z_0}} \cdot v' \right) \right)}{B \cdot n \cdot (273 + t) \cdot r_k \cdot (N_a + N_k + N_{ka}) \cdot x} \tag{28}$$

Table 1: Whirlpool losses (Ozdamar and Kavas, 1999)

λ	5	6	7	8	9	10
$Cp_{Schmitz}$	0.550	0.555	0.559	0.563	0.566	0.568

Table 2: Technical features related to the wind turbines selected

Parameter	WT-1	WT-2	WT-3	WT-4
Radius of the rotor (m)	25	20	15	3.5
Height for which we want to learn the wind speed (m)	50	40	25	20
Number of blades on the rotor	3	3	3	3
Rotation number of the rotor (rpm)	26	22	18	250

Table 3: Data accepted in the three plants

Parameter	Plant A	Plant B	Plant C
Maximum illuminating power (W)	1,000	4,000	10,000
Maximum force power (W)	5,000	30,000	120,000
Lost power in the network (W)	200	1,000	2,000
Reserve coefficient	1.2	1.3	1.5
Development factor	1.0	1.2	1.5

Table 4: The other data of accepted features

Accepted feature	Accepted value
Height for which we know the wind speed (m)	10
Wind speed at a known height (m s^{-1})	8
Roughness coefficient of earth originating from the obstacles	0.3
The lift coefficient of the profile	1.5
Air temperature (°C)	20
Mechanical efficiency of the wind turbines (%)	0.80

This equation is the final one which can be used towards determining the electrical energy demand of a plant via a single wind turbine.

A point should be remembered here is the development factor. It should be designed beforehand that to which extent the plant will develop in the future and how much electrical energy will be needed. For instance, if it is planned that the plant will an extra energy demand of 20% in the future, then the development factor should be 1.2, or if it is thought that an extra energy of 50% will be needed, the development factor should be 1.5.

Four types of wind turbines and three different plant types were considered in the project. Technical characteristics of wind turbines are given in Table 2. Calculations related to meeting the energy demands in the plants A, B and C using the data related to the turbines mentioned. Data related to the plants A, B and C are given in Table 3. Other accepted data are given in Table 4.

RESULTS AND DISCUSSION

The aim of this study is meeting the electrical energy demand of a plant by establishing a wind turbine. Determination of the energy values produced by a wind turbine was explained in the mathematical equations given in the methods section, as well as the determination of the energy values needed by the plants.

Results related to the wind turbine powers calculated depending on the above data and the power values demanded by the plants are given in Table 5 and 6, respectively.

When the research results are examined, it can be seen that the wind turbine coded WT-4 is suitable, while the others are not suitable since they produce much more energy than demanded by the plant (Table 7).

Table 5: Results related to the wind turbine powers

Wind turbines	Power accepted form the wind turbine (kW)
WT-1	829.89
WT-2	455.29
WT-3	186.76
WT-4	9.22

Table 6: Power values demanded by the plants

Plants	Power values demanded by the plants (kW)
A	7.44
B	45.50
C	183.00

Table 7: The meeting ratio of the selected wind turbines the power demanded by the plant A, B and C

Wind turbine code	Plant A	Plant B	Plant C
WT-1	111.5	15.2	3
WT-2	61.2	8.3	1.66
WT-3	25.1	3.4	0.68
WT-4	1.2	0.17	0.03

When the plant B is examined, it can be seen that the wind turbine coded WT-4 can meet only 17% of the energy demanded by the plant, hence, is not suitable (Table 7). The wind turbines coded WT-1 and WT-2 produce energy much higher than the energy demand of the plant B, while the wind turbine coded WT-3 produces energy 3.4 fold of the energy demand of plant B. it will be more suitable to establish a wind turbine having a capacity between WT-3 and WT-4.

When the plant C is examined, we can see that the wind turbine coded WT-4 can only meet 3% of the demand of the plant, while the turbine coded WT-3 can meet 68% (Table 7). The turbine coded WT-1 can produce 3 times the energy demand of the plant C, whereas the wind turbine coded WT-2 has the capacity to produce 1.66 times the demand of C plant. The wind turbine coded WT-2 may be preferred for the plant C. However, a wind turbine with a capacity between those of the turbines WT-3 and WT-2 will be more suitable for the plant.

The results obtained indicated that, selection of a wind turbine could be done easily by evaluating the energy requirements of each plant with the aid of the mathematical equations given in the methods section. The power values obtained from the wind turbines in the studies made so far are similar to those obtained from this study. For instance, it was reported in a study by Klug (2001) that wind turbines with the rotor diameters of 15, 30, 37 and 44 m had the approximate power values of 50, 300, 500 and 600 kW, respectively. In another study by Ender (2005), the power values of wind turbines with the rotor diameters of 0-16, 16-45 and 45-128 m were 10-60, 130-750 and 1500-6400 kW, respectively. Data of the wind turbine manufacturers support the results obtained from this study. The rotor diameter and the power value of 43/600 model wind turbines manufactured by Nordex (2005) and Jacobs Energie (2005) companies are 43 m and 600 kW, respectively. Wind turbines with the rotor diameters of 2.5 m and 7 m produced by the company Bergey Wind Power (2005) are 1 and 10 kW, respectively.

Plants who intend to take benefit of wind energy can select the optimum wind turbine for their own needs by using the data calculated in this study. In this way, unnecessary investment costs will be avoided.

CONCLUSIONS

This study showed that it was possible to determine whether the wind turbine to be established was suitable for the plant via putting in the established power of the plant, the wind potential in the area intended for the establishment of a wind turbine and the characteristics of wind turbine rotor in a single equation.

When the suggestions stated in this study are implemented, the meeting ratio of the power that can be obtained from the wind turbine the established power of the plant (MR) to be at least 1. The results below this value indicate that the wind turbine intended is not suitable for the plant.

Some data should absolutely be revealed beforehand, if it is intended to utilise wind energy in a given region. These include factors such as the wind potential of the region, the prevalent wind direction, distribution of the wind in time. It should be well evaluated whether the electrical power demanded by the plant can be met, considering these factors. Otherwise, the investment put on the wind turbine may be a dead-born one. An investment which does not meet the need of the plant urges the plant-owner to get external electrical energy. This means an extra cost.

This study was established in a way that especially the plants intending to utilise wind energy could pattern after. It is possible for the plants to determine the suitable wind turbines for themselves by putting their own data in the mathematical equations. For this purpose, they should reveal the data of the plant. Thereafter, a wind turbine that can generate the energy demanded by the plant should be determined. The power that the wind turbine will generate may be determined by putting the data related to the wind turbine selected in the Eq. 25. It is also possible to find at which rate the wind turbine selected will meet the energy demand of the plant by putting the data related to the plant and to the wind turbine in the Eq. 28.

NOMENCLATURE

N	The establishment power of the plant (W),
ρ	Air density (kg m^{-3}),
η	Mechanical efficiency of the wind turbine (%),
ϵ	Slide number (--),
λ	Tip speed ratio (--),
$\eta_{profile}$	Profile losses (--),
η_{tip}	Tip losses (--),
A	Cross-section area (m^2),
B	Number of blades on the rotor (--),
C_D	The drag coefficient of the profile (--),
C_L	The lift coefficient of the profile (--),
Cp	The optimum power coefficient of the rotor (--),
$Cp_{Schmitz}$	Whirlpool losses (--),
E	Kinetic energy of the wind (Nm),
v	Wind speed at a known height (m s^{-1}),
v'	Wind speed at the desired height (m s^{-1}).
h	Height for which we know the wind speed (m),
h'	Height for which we want to learn the wind speed (m),

z_0 Roughness coefficient of earth originating from the obstacles (--),
MR The rate at which the power that can be obtained from the wind turbine meets the establishment power of the plant (%),
m Mass of air (kg m^{-3}),
k Von Karman constant (0.4),
N_a Maximum illuminating power (W),
N_k Maximum force power (W),
N_{ka} Lost power in the network (W),
N_{max} Point power (maximum consumption power) (W),
N_y Alternate power (W),
u* Wind speed height factor (--),
P Power that can be obtained from the wind speed (W),
r Radius of the rotor (m),
r_k Reserve coefficient (--),
T Time (s),
t Air temperature (°C),
n Rotation number of the rotor (rpm),
x Development factor (1.0 .... ∞),

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