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Calculation Model of Wind Energy Output Based on Capacity Factor

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Abstract. The capacity factor shows the annual energy output efficiency of a wind turbine and can be used to evaluate the operation performance of the wind turbine. In this paper, we use the capacity factor to study the operation performance of wind turbines. Firstly, based on the wind speed conditions and the performance parameters of wind turbine devices, the revenue and cost of a wind energy project are calculated. The calculation formula of economic capacity factor is derived by breakeven analysis of the revenue and cost. Secondly, considering different machine types and wind speeds, a simplified physical calculation formula of physical capacity factor is developed. Finally, a case study with actual data in a specified area is presented. The values of economic and physical capacity factors are provided. The differences between them are discussed in detail. The relationship between the mean wind speed and capacity factor is discussed. The result provides a new quantitative basis for selecting wind turbine and farm which are suitable for territorial wind speed conditions.

Introduction

Nowadays, the proportion of renewable energy resources is increased in China. Wind energy became a fast growing alternative energy source. “The China wind power development roadmap 2020” indicates that by the year 2020 the installed capacity of wind power will reach 0.2 billion kW. According to this national planning, the stake electrovalence of wind power will be equivalent to that of coal power by the year 2020.The stake state electrovalence of wind power will decrease from 0.6 ￥/kWh to 0.4 ￥/kWh. Therefore, in order to ensure the price competitiveness, improving the investment efficiency and operation benefit of wind energy project is a key problem.

There are some researches on the location selection of wind power farms, type selection of wind turbines and calculation model of wind energy output. Wenjun Zhang et. al [1] claim that the generated energy by wind is related to the wind energy potential and the performance of wind turbines. The generated energy is closely related to economic benefits. Paper [2] assesses the wind energy potential for a given location and selects the wind turbine by using costs of kWh wind-generated electricity. Paper [3] uses chance constrained programming and montecarlo method to obtain the optimal installed capacity by considering the maximum economic benefit of wind farms. Paper [4] provides the optimum selection of rated wind speed for wind turbine, and presents that the increasing wind turbine diameter can increase the economic benefit. These papers propose the influence of wind speed condition and wind turbine performance on the economic benefit. The indexes used in these papers are mostly net present value and the cost of kWh wind-generated electricity. Paper [5] proposes the properties of capacity factor. A higher capacity factor value shows that the exploitation of the wind potential for the specific site is better. Paper [6] suggestes that the capacity factor depends on the site of wind energy farm and the machine model.

This paper calculates the revenue and cost of the wind energy project based on the existing literatures, obtains the economic capacity factor by breakeven analysis based on the influencing factors of the capacity factor, and estimeats the physical capacity factor at different machine models and different wind speeds. On this basis, this paper presents a case study to derive the relationship between the mean wind speed and capacity factor. The result provides a new quantitative basis for the wind turbine selection and wind farm location selection.

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Methodology

Before modeling, we made the following assumptions : the cost and revenue which we estimate are annual values. The annual mean of wind speed is calcated by the wind speed at the certain hub height.

The capacity factor. The capacity factor (C_F) is the ratio between the power produced by wind turbines and the total power of the full capacity. It can be expressed as [6]:

$$C_F = E_t / tP_R \tag{1}$$

where t is the running time of wind turbine, E_t is the generated energy for t time, P_R is the rated power of the wind turbine.

Rated power and cost. The cost of the wind energy project consists of the initial investment cost (C_i) and the operation and maintenance costs (C_{om}). C_i can be calculated as follows [7]

$$C_i = (1 + \lambda_1)P_R \times C_{PR} \tag{2}$$

where P_R and C_{PR} are the rated power of wind turbines and specific costs , and λ_1 is the ratio of other initial costs.

The operation and maintenance costs of wind energy consist of salary, depreciation costs and maintenance costs. The salary (C_S) can be expressed as [7, 8].

$$C_s = nC_{ep}P_R \tag{3}$$

Where n is the staff number of unit rated power, C_{ep} is the annual average salary of per staff, and P_R is the rated power of the wind turbine.

The depreciation costs (C_D) can be determined by the straight-line depreciation method as [7, 8]:

$$C_D = \frac{C_{wt}(1 - S)}{T} = \frac{P_R \times C_{PR}(1 - S)}{T} \tag{4}$$

where S and T are, respectively, the ratio of remaining value and depreciation life. C_{wt} is the wind turbine cost as seen in Eq. 2.

The maintenance cost (C_M) can be expressed as a percentage of the initial investment cost as Eq.5[7,8].where λ_2 is the ratio of the maintenance cost to the initial investment cost .

$$C_m = \lambda_2 C_i = \lambda_2(1 + \lambda_1) \times P_R \times C_{PR} \tag{5}$$

The annual cost of operation period (C) can be determined by the following equation:

$$C = C_w + C_D + C_m = P_R \times \left[nC_{ep} + \frac{C_{PR}(1 - S)}{T} + \lambda_2(1 + \lambda_1)C_{PR} \right] \tag{6}$$

Let μ_1 be the following expression Eq.7. Finally, the cost of wind energy can be expressed as Eq.8.

$$\mu_1 = nC_{ep} + \frac{C_{PR}(1 - S)}{T} + \lambda_2(1 + \lambda_1)C_{PR} \tag{7}$$

$$C = \mu_1 P_R \tag{8}$$

Revenue and profits. The revenue of wind energy project (R) is mainly the power selling income which can be expressed as Eq.9[8].Where P_e is the stake electrovalence of wind energy (\$/kWh), E_t is the production capability for t time (kWh).

$$R = P_e \times E_t \tag{9}$$

The profit of wind energy project can be determined by the gap between the cost and the revenue, which is denoted as follows:

$$P = R - C = P_e \times E - \mu_1 P_R \tag{10}$$

The capacity factor under breakeven analysis. In the breakeven analysis, the revenue and cost are equivalent. Substitute Eq.10 into Eq.1, the capacity factor under breakeven analysis (EC_F) can be calculated as Eq.11. Let EC_F be the economic capacity factor.

$$EC_F = \mu_1 / (tP_e) \tag{11}$$

The physical capacity factor. The capacity factor can be calculated by the mean wind speed of wind farms and the power curve of wind turbines [8]. Let this capacity factor be the physical capacity factor (PC_F). In this case, the physical generated energy (PE_t) can be expressed as follows:

$$PE_t = t \times P_{Vm} \qquad (12)$$

where P_{vm} is the wind generator power output at the mean wind speed.

Substitute Eq. 12 into Eq.1, PC_F can be expressed as:

$$PC_F = \frac{PE_t}{tP_R} = \frac{P_{Vm}}{P_R} = \begin{cases} 0 & else \\ \frac{1}{V_R^3 - V_I^3} V_m^3 - \frac{V_I^3}{V_R^3 - V_I^3} & V_I \le V_m \le V_R \\ 1 & V_R \le V_m \le V_O \end{cases} \qquad (13)$$

where V_R is the rated speed, V_I is the cut-in speed, V_O is the cut-out speed and P_R is the rated power.

Case analysis

The parameter values are essential in calculating EC_F and PC_F as shown in Table 1. Some parameter values are referred to the existing literature. Others are estimated based on the economic condition.

Table 1 The parameter values

The parameter name	The specific value	The parameter name	The specific value
C_{PR} （￥/Kw）	5100[7]	λ_1	30%[7]
n	0.003	λ_2	6%[7]
C_{ep}（￥）	20000	t（h）	8760
S	10%[7]	P_e（￥/kWh）	0.51[8]
T (year)	20[7]		

EC_F can be calculated based on Table 1 and Eq.11 as follows:

$$EC_F = 0.154 \qquad (14)$$

Wind turbine models with three sizes and rated power ranging from 1000 kW to 2500 kW are chosen from different manufactures to simulate their PC_F. The specification of selected wind turbines are given in Table 2.

Table 2 Specification of considered wind turbines

Wind turbine Model	Cut-in speed （m/s）	Cut-out speed （m/s）	Rated speed （m/s）	Rated power (kW)
1	3.5	25	13	2500
2	4	23	14	2000
3	3	25	15	1000

The mean wind speed between cut-in speed and rated speed is chosen to calculate PC_F. According to Table 2, the PC_F of the selected wind turbines can be calculated as follows:

$$PC_{F1} = \frac{1}{2454.125} V_m^3 - \frac{42.975}{2454.125} \qquad (15)$$

$$PC_{F2} = \frac{1}{2690} V_m^3 - \frac{64}{2690} \qquad (16) \qquad PC_{F3} = \frac{1}{3349} V_m^3 - \frac{27}{3349} \qquad (17)$$

The relationship between the mean wind speed and capacity factor of different wind turbines is plotted in Fig.1.

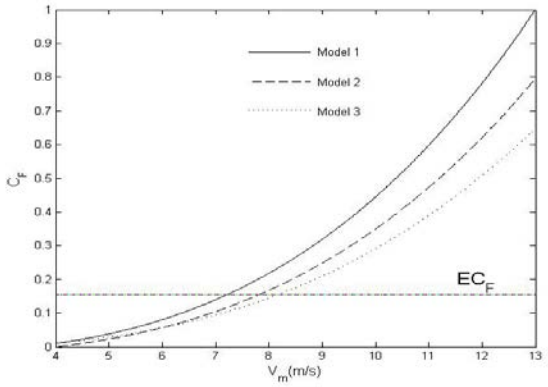

Fig.1 the relationship between wind speed and C_F

Results and discussion

Fig.1 shows the difference between EC_F and PC_F.。 The lowest mean wind speed of each wind turbine is calculated by breakeven analysis. Define this mean wind speed as economic mean wind speed. According to Fig.1, the economic mean wind speed of three wind turbines are 7.21 m/s, 7.81 m/s and 8.16m/s respectively. The wind turbine can be chosen if the actual mean wind speed is higher than the economic mean wind speed of the wind turbine. If the wind speed of all of the wind turbines can't reach the mean wind speed, this site is improper for building a new wind power plant.

The result shows that EC_F depends on the specific cost of wind turbines, the wages level of the location site and the stake electrovalence of wind energy. EC_F in different sites is different. PC_F is related to the performance of wind turbine and the wind speed condition. PC_F depends on the cut-in speed and rated speed of the wind wind turbine. For same machine, the PC_F is higher with larger mean wind speed.

Conclusion

It should be noted that the proposed approach aims at discussing the calculation model of Wind Energy Output. This paper takes wind speed conditions and wind turbine performances into consideration, calculates the ECF and PCF, and obtains the relationship between the mean wind speed and capacity factor. The results of this paper provide a new quantitative basis for wind turbine selections and wind farm location selections.

The effect of the stake electrovalence changing and subsidy policy on capacity factor should be considered as a further study in order to obtain overall conclusion.

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