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SELECTION AND ECONOMIC VIABILITY OF WIND TURBINES

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ABSTRACT

Wind turbine power depends primarily on wind speed and turbine rotor diameter. Thus, different turbine designs may be applied in order to achieve the same amount of turbine nominal power. The rotor diameter has to be large when the nominal wind speed is low, and vice versa: the appropriate rotor diameter should ideally be much smaller at high nominal wind speeds. From the point of view of turbine costs, small turbine dimensions are favorable, however, in this case the average wind speed at the selected location should be high enough in order to assure the appropriate share of turbine operations at nominal power conditions. Otherwise the annually produced amount of electric energy will be too low for the turbine to be cost effective. Thus it is very important to select an appropriate turbine design for the selected location. Every location has its own wind speed characteristics, and these should be well known before a turbine is selected. The most reliable are the results obtained by the instantaneous wind speed measurements over a longer period of time, i.e. at least six months. Since this procedure is very expensive and time consuming, wind speed fluctuation modeling is often used. One of the simplest models applies Weibull distribution, which allows the wind speed frequency distribution to be obtained when only the average wind speed and specific terrain characteristics of the selected location are known. Using the wind speed frequency distribution, the produced energy distribution is easy to obtain from the turbine wind speed-power curve, and after the integration, the amount of annually produced energy can be determined. An example of turbine selection and economic viability analysis is presented in the paper. The wind speed frequency distribution was modeled by Weibull distribution for three different sites and an optimal turbine gaining the highest produced energy to capital costs ratio and the lowest levelized cost of electricity was selected for each site.

Keywords: wind turbine, wind speed distribution, economic viability

1. INTRODUCTION

Wind turbine power increases with the third power of wind speed and the second power of the turbine rotor diameter [1]. Thus, a different turbine design may be applied in order to achieve the same nominal turbine power. The rotor diameter has to be large when the nominal wind speed is low, and vice versa: the appropriate rotor diameter is ideally much smaller at higher nominal wind speeds. From the capital costs point of view, small turbine dimensions are favorable, however, in this case the average wind speed at the selected location should be high enough in order to assure the appropriate share of turbine operation at nominal power conditions. Otherwise the amount of electric energy that is produced annually will be too low for the turbine to be cost effective. Thus, it is very important to select an appropriate turbine design for the selected location. An example of turbine selection and economic viability analysis is presented in this paper. Different turbines with their specific wind speed-power curves were compared. The wind speed frequency distribution was modeled via Weibull distribution [2] for three different sites and subsequently an optimal turbine with the highest produced-energy-to-capital-costs ratio was selected for each site.

2. WIND TURBINE CHARACTERISTICS

Four wind turbines produced by Enercon were compared in this study. Fig. 1 presents their power curves while some further details are given in Table 1. All four turbines have the same nominal power. However, their diameters differ considerably. The swept area of the E-103 turbine is more than twice as large as the swept area of an E-70 turbine. Thus, its capital costs are higher too. A simple equation was used to correlate the turbine costs with its diameter:

$$I = I_0 + I_D = I_0 + i_D \cdot D^2 \qquad \text{... (1)}$$

where I = turbine costs, I_0 = elementary costs, I_D = rotor diameter influenced costs, i_D = correlation factor, D = rotor diameter. For the set of turbines listed in Table 1, the approximate values are I_0 = 1.5M€ and i_D = 235€/m^2. The capital costs calculated by Eq. (1) are listed in Table 1.

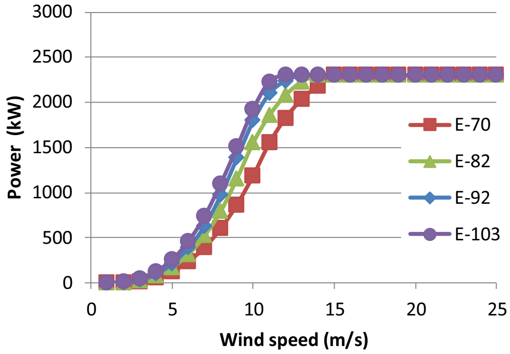


Figure 1. Wind turbine power curves

Table 1. Overview of wind turbines technical details

Turbine	E-70	E-82	E-92	E-103
Nominal power (kW)	2350	2350	2350	2350
Rotor diameter (m)	71	82	92	103
Start-up w. speed (m/s)	2	2	2	2.5
Nom. wind speed (m/s)	15.5	14	13	12
Max. wind speed (m/s)	25	25	25	25
Swept area (m^2)	3960	5281	6648	8333
Capital costs (€)	2.7M	3.1M	3.5M	4.0M

3. WIND SPEED CHARACTERISTICS

Any location has its own wind speed characteristics, and these should be well known before a turbine is selected. The most reliable are the results obtained by the instantaneous wind speed measurements over a longer period that is at least six months. Since this procedure is very expensive and time consuming, wind speed fluctuation modeling is often used. One of the simplest models applies a Weibull distribution, which allows the wind speed frequency distribution to be obtained when only average wind speed and the specific terrain characteristics of the selected location are known. When using Weibull distribution, wind speed frequency distribution may be written as [2]:

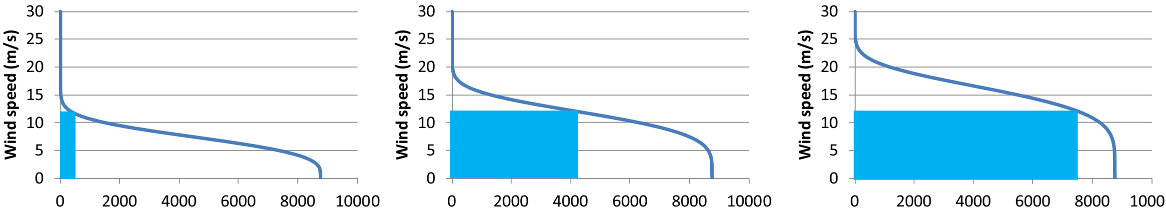
$$p(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^{k}} \qquad \text{... (2)}$$

where $p(v)$ = probability of wind speed, v = wind speed, c = scale factor, k = shape factor. Both factors c and k are constants dependent on local wind conditions. They may be evaluated experimentally or by using different correlations, such as [3]:

$$c = \frac{2 \cdot v_m}{\sqrt{\pi}} \qquad k = \left(\frac{\sigma_v}{v_m}\right)^{-1,09} \qquad \text{... (3)}$$

where v_m = average wind speed and σ_m = standard deviation of wind speed.

Three locations A, B and C with different wind speed characteristics were selected for comparison. Figure 2 shows wind speed distribution curves for each location. A rectangle has been drawn into each diagram. Its height corresponds to the nominal wind speed of the E-103 turbine (v_n = 12 m/s – see Table 1). Therefore, its length shows the maximum possible time period within which the E-103 turbine can operate at nominal power. At site A, this can happen less than 400 hours per year, while at site C the same turbine can operate at nominal power for more than 7,500 hours per year. However, in the latter case, a lot of energy remains unharvested and turbines with higher nominal speeds may perform better. However, the question is which of them is optimal, especially from an economic point of view.



Site A: v_m = 7 m/s, σ_v = 2,5 m/s **Site B**: v_m = 11 m/s, σ_v = 3 m/s **Site C**: v_m = 15 m/s, σ_v = 3,5 m/s

Figure 2. Wind speed distribution curves

4. ANNUAL ENERGY PRODUCTION

The amount of annually gained energy by a specific turbine operating at the selected location can be predicted by employing wind turbine power and wind speed distribution curves, respectively. Using the wind speed frequency distribution, produced energy distribution is easy to obtain from the turbine wind speed-power curve, and after the integration, the amount of annually produced energy can be determined. Fig. 3a shows the amount of predicted annually harvested energy by different wind turbine at all three selected sites. Electricity production is the highest with the larger turbine E-103 at all three sites. At site C, with an average wind speed of 15 m/s, turbine E-103 yields almost 20,000 MWh per year, while the same turbine produces only 8,000 MWh per year at site A with an average wind speed of 7 m/s. Smaller turbines harvest less energy. However, the differences decline when the average wind speed is increased. The smallest E-70 turbine produces only 60% of the energy produced by the E-103 turbine at site A, while at site C the ratio increases to 93.4% (Fig 3b).

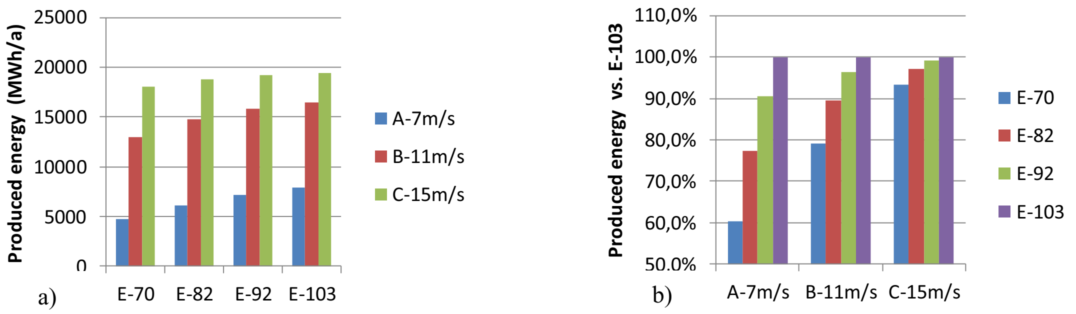


Figure 3. Annually produced energy (a) and produced energy vs. E-103 (b)

5. ECONOMIC COMPARISON

Capital costs play an important role when the economic viability of any power plant is analyzed. One of the rule of thumb parameters that can be used in the economic comparison of different wind turbines is the gained energy to capital cost ratio (EIR). Figure 4a shows the resulted EIR for a considered set of turbines and locations. Although the turbine E-103 produces the highest amount of electric energy at all three locations, its EIR is the highest only at site A, where the average wind speed is the lowest and the investment into a large turbine results in high EIR. At both other locations, where the average wind speed is higher, the EIR of E-103 turbine is the lowest of all turbines due to its high capital costs. Similar results are obtained when the levelized cost of electricity (LCOE) is applied for economic comparison. In this case, not only is the capital cost of a turbine installation considered, but also the annual capital charge rate. This is calculated by converting the capital cost plus any interest payable into the equivalent annual costs using the concept of 'annuitization' [4]. Furthermore, the operation and maintenance costs and the period (number of years) over which the investment is to be recovered are also considered. Figure 4b shows the predicted LCOE for all turbine and site combinations. LCOE was calculated using a 7% discount rate and an amortization period of 15 years. The annual operating costs were estimating as 2.5% of the capital costs according to the European Wind Energy Association. A comparison shows the very high influence of average wind speed on LCOE, especially in the low to moderate wind speed range. Differences in LCOE caused by a specific turbine are much smaller and amount to only 1.5 EUR/MWh at site B, while at site A, there is almost a 20 EUR/MWh difference between the lowest and the highest LCOE.

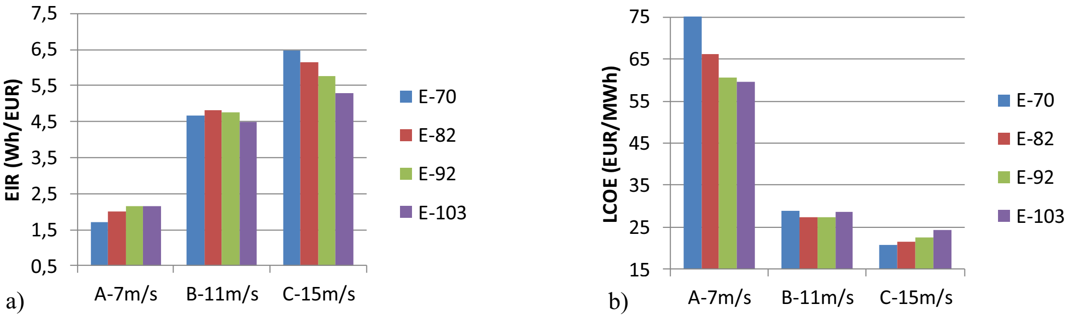


Figure 4. Predicted gained energy to capital cost ratio (a) and levelized cost of electricity (b)

6. CONCLUSIONS

This study presented a simple procedure for the economic evaluation of different wind turbines at locations with dissimilar wind speed characteristics. Four different wind turbines in combination with three sites were compared. All turbines have the same nominal power, however, their nominal wind speed differs, thus rotor diameter and consequently turbine swept area were different and thus so were the turbine capital costs. It was shown that the turbine with the largest swept area and the lowest nominal wind speed yielded the highest annual amount of energy at all three sites, however, only at the site with the lowest average wind speed does this also lead to the best economical result of all turbines, i.e. the lowest LCOE, which is influenced by both the wind conditions and by the turbine selection. The latter is especially important at low wind speed conditions, while at moderate to high wind speed conditions, LCOE does not depend much on the selected turbine.

7. REFERENCES

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