Assignment – Wind energy

OE44170 –Offshore Renewable Technologies 2025

Part 1: The Wind Resource [45 pts]

For this part you will consider some real, local wind speeds, to get an idea of its probability distribution. To do this, each group will use a set of hourly windspeed data for the year 2024 taken at 10 m height . Decide on the parameters and download the data from **[1]**. Consider some basic statistical properties of the wind speed dataset.

- What is the average wind speed U? *[2.5 pts]*
- The standard deviation of the wind speed data? *[2.5 pts]*

- Plot a histogram of the wind speeds (with wind speed intervals of 1 m/s), normalized so as to represent the probability density function. *[10 pts]*
- Use the graphical method, also known as method of least squares, see *Appendix 1,* to estimate the two parameters of the Weibull distribution (shape factor k and scale factor c) for your dataset. *[20 pts]*
- Indicate the coefficient of determination R^2 for the linear regression used in the previous point. Add a plot of the estimated Weibull distribution to your histogram. *[5 pts]*
- Using the estimated Weibull distribution, compute the Root Mean Square Error (*RMSE*) with respect to the dataset. Write a short reflection on the values found, how do you interpret them. *[5 pts]*

Part 2: Wind energy production [35 pts]

Consider the following (reference) wind turbines and their respective key parameters. The power curves can be found in the following .csv files obtained from **[2]**. (files available in Brightspace).

- BAR_LowSP_6.5MW_234.csv
- IEA_10MW_198_RWT.csv
- IEA_15MW_240_RWT.csv

Item	WTG 1	WTG 2	WTG 3	Units
Name	BAR LowSP 6.5MW	IEA 10 MW RWT	IEA 15 MW RWT	N/A
Rated Power	6500	10000	15000	kW
Rated Wind Speed	8.5	11	10.6	m/s
Cut-in Wind Speed	4	4	3	m/s
Cut-out Wind Speed	25	25	25	m/s
Rotor Diameter	234	198	240	m
Hub Height	150	119	150	m
Drivetrain	-	Direct Drive	Direct Drive	N/A
Control	-	Pitch Regulation	Pitch Regulation	N/A
IEC Class	-	IA	1B	N/A

- Choose two turbines and plot their power curves. *[5 pts]*
- Adjust your hourly wind speed dataset to the hub height of each of the turbines using the logarithmic extrapolation method (for the sake of simplicity, you can neglect atmospheric stability effects). You can use the wind speed dataset at 50 m height to obtain the roughness length. *[10 pts]*
- Calculate the Annual Energy Yield (AEY) and the capacity factor (CF) for the selected turbines and your site from part 1. Note that each turbine has different operational characteristics. *[10 pts]*
- Between the two selected turbines which one would you recommend to be used for your given site, justify your answer. *[10 pts]*

Part 3: Wind turbine technology [20 pts]

Assume an offshore wind turbine with a rotor diameter of 220 m and rated power of 14.1 MWe at 11 m/s. At rated power the drivetrain has an overall efficiency of 97% (mechanical to electrical conversion). The performance of the aerodynamic rotor can be found on *Appendix 2*. Consider an air density of ρ_{air}=1.205 [kg m^{-3}].

- If the wind speed is 10 m/s and the speed after the turbine is 7 m/s, what is the power coefficient of this wind turbine? *[5 pts]*
- When the wind speed is 15 m/s, the rotor rotates at a constant angular velocity of 7.8 rpm. Calculate the tip to speed ratio and power coefficient of this model. *[5 pts]*
- What do you expect about the power extraction coefficient of the model in question when the wind speed is at 9 m/s? the rotor rotates at 5.4 rpm. *[5 pts]*
- What is the thrust force that the rotor will exert on the top of the tower, when operating at rated conditions? *[5 pts]*

Appendix 1: Estimation of Weibull parameters via the Method of Least Squares

The graphical method is achieved through the cumulative distribution function. In this method, the wind speed data are interpolated by a straight line, using the concept of least squares after a double logarithmic transformation **[3]**.

First, note that the cumulative distribution function of a Weibull distribution can be expressed as follows:

$$F(v) = \int_0^v f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)^k}$$

Thus:

$$1 - F(v) = e^{-\left(\frac{v}{c}\right)^k}$$

Taking the natural logarithm of both sides of the equation yields the equation

$$\ln\left(1 - F(v)\right) = -\left(\frac{v}{c}\right)^k$$

Multiplying both sides of the equation by -1 and then taking the log again yields the equation

$$\ln\left(-\ln\left(1 - F(v)\right)\right) = k \ln v - k \ln c$$

This can be expressed as the linear equation

$$y = ax + b$$

Where $\mathrm{y} = \ln\left(-\ln\left(1 - F(v)\right)\right)$, $\mathrm{x} = \ln v$, and $b = -k \ln c$.

The value of the slope (a), and therefore the shape factor, can be obtained:

$$a = k = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

The value of (b) can be obtained as:

$$b = \frac{\sum_{i=1}^{n} y_i \sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

And the scale factor is calculated as:

$$c = e^{-\left(\frac{b}{a}\right)}$$

Thus if the sample has a Weibull distribution, then we should be able to find the coefficients a and b via linear regression.

Appendix 2: The aerodynamic power

The aerodynamic power that is captured by the turbine-rotor from the kinetic energy of the wind can be obtained from:

$$P_{aero}(t) = C_P \frac{1}{2} \rho_{air} \pi R^2 {U_{wind}}^3$$

Where U_{wind} is the average wind speed at hub height and the dimensionless power coefficient C_P is a function of the operating characteristics of the turbine, namely the tip speed ratio $\lambda = \frac{\omega R}{U_{wind}}$ and collective pitch angle of the blades β.

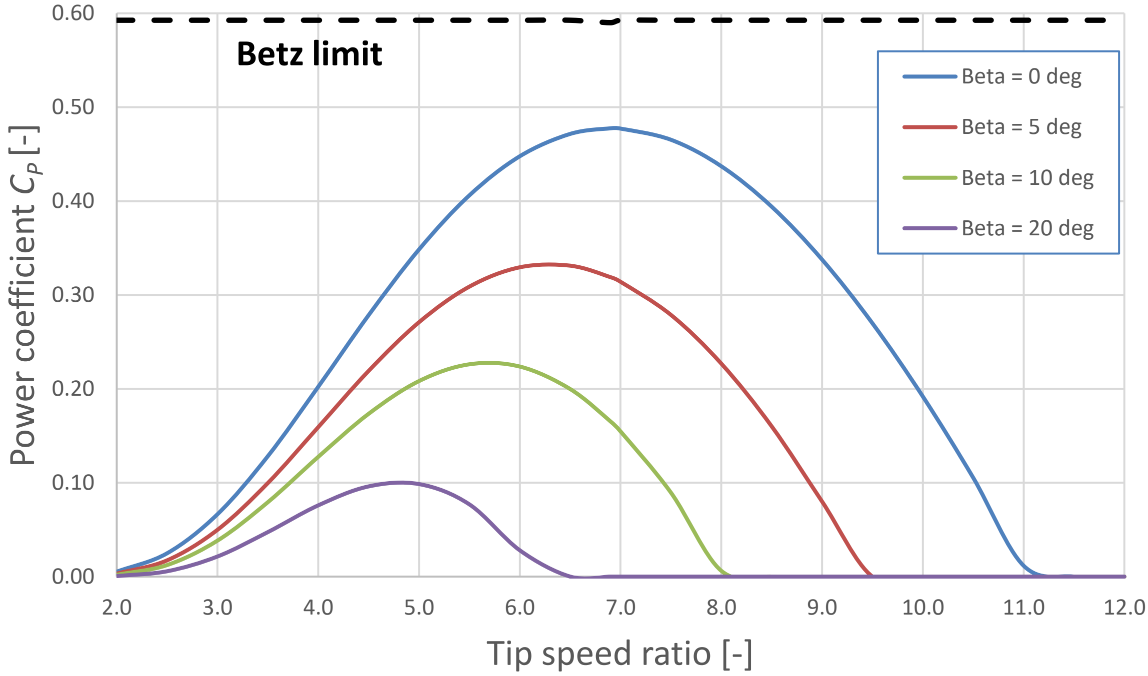
The power coefficient can be utilized in the form of look-up tables or in form of a function. An empirical description of the power coefficient for a particular three bladed horizontal axis wind turbine, can be described by using the following relations **[4]**.

$$C_P(\beta, \lambda_i) = 0.79\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda_i}}$$

$$\lambda_i = \frac{1}{\frac{1}{(\lambda - 0.02\beta)} - \frac{0.003}{(\beta^3 + 1)}}$$

Where β is in degrees, and the maximum power efficient of 0.48 occurs for $\beta = 0$ degres at the design tip speed ratio of 6.9, such that

$$C_{Pmax}(0, \lambda_{opt}) = 0.48 \ \ with \ \ \lambda_{opt} = 6.9$$



Disclaimer: Note that the coefficients in the empirical expression have been adapted from reference **[4]** and slightly modified to reflect the increased aerodynamic performance of modern wind turbines. It is not recommended to use this expression outside the context of this assignment or as a generic relation. The coefficients of the function depend on rotor type and blade geometry, and can be different for various wind turbines.

References:

[1] *NASA Prediction of Worldwide Energy Resource* - https://power.larc.nasa.gov/

[2] *NREL Wind Turbine Power Curve Archive* - https://nrel.github.io/turbine-models/index.html

[3] *Rocha, P. A. C., de Sousa, R. C., de Andrade, C. F., & da Silva, M. E. V. (2012). Comparison of seven numerical methods for determining Weibull parameters for wind energy generation in the northeast region of Brazil. Applied Energy, 89(1), 395-400.* https://doi.org/10.1016/j.apenergy.2011.08.003

[4] *Slootweg, J. G., De Haan, S. W. H., Polinder, H., & Kling, W. L. (2003). General model for representing variable speed wind turbines in power system dynamics simulations. IEEE Transactions on power systems, 18(1), 144-151.* https://doi.org/10.1109/TPWRS.2002.807113