Project Exercise 1
Comparing the performance of a 3 MW wind turbines at a prospective site

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ENE416-G 23H Wind Energy

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Introduction

Wind energy and importance in world energy production

Wind energy is currently a critical resource in our society on account of its multiple advantages. In the first place, wind energy is a sustainable solution to our energy requirements because it is a pure and renewable energy source. Wind energy does not contribute to climate change or generate detrimental emissions, in contrast to fossil fuels. It aids in environmental preservation for future generations and cuts down our carbon footprint[1]. Additionally, wind energy reduces our reliance on finite resources such as oil and gas by contributing to the diversification of our energy sources. Furthermore, wind energy promotes a green economy and facilitates economic expansion by generating employment opportunities. It is a win-win circumstance in which we can generate electricity and safeguard the environment. Harnessing wind energy is an essential stride in the direction of a more environmentally conscious and sustainable future[2].

Wind turbine technology

A wind turbine is a mechanical device that transforms the kinetic energy of the wind into rotational energy. The mechanical energy can then be converted to electrical energy by a generator, which can then supply an electrical grid. The performance of a wind turbine is influenced by its ability to capture and convert the kinetic energy of wind into usable electrical energy. As such, it is crucial to evaluate the efficiency, reliability, and overall performance of different turbine models to make an informed decision. The frequency of energy output is dictated by the rotational speed of the generator, which can be regulated through a gear system[3].

Wind resource at particular Site

The selection of a site is critical to the effective execution of wind energy projects. It involves taking into account a variety of parameters to achieve optimal energy output, cost-effectiveness, and environmental compatibility. The first issue to consider is wind resource, Probability distributions of wind, Energy density, most frequent wind velocity and velocity corresponding to maximum energy. Furthermore, access to existing electrical grids is critical for optimal power system integration. Environmental factors, such as wildlife and habitat impacts, must also be considered to ensure long-term growth. Developers may capture the full potential of wind energy, contribute to clean and renewable power generation, and pave the road for a more sustainable future by selecting the correct site. Selecting a turbine that is compatible with the site's wind resource guarantees that it will be able to continuously produce power at its rated capacity. By doing this, it becomes less likely that the turbine will be underutilized or exposed to strong winds, which could result in decreased efficiency or even damage[4].

Objective of this project

To model and simulate the performances of 5 different wind turbines of 3MW rated capacity a site of your interest and compare the performances to identify the best turbine for the project.

Theory and Methodology

Step 1: Identification of Prospective Site:

1. Get the historical data of the selected place from **Open Meteo**[5]. In this case we have selected the Utsira Norway[6].
2. Taking the wind speed at 100m for 5 years.
3. The data of this site can be found at appendix A.

Fig.1. Website of Open Meteo

Step 2: Calculation of Weibull K and C for the sites wind spectra:

1. Calculation of average wind speed and standard deviation.(Appendix A)

   Average Wind Speed: The average wind velocity during a given period may differ contingent upon the geographical location and time period under consideration. Wind velocities are susceptible to variation throughout the day, month, and year as a result of a number of factors, including topography, weather patterns, and seasonal changes. The average wind speed can be found by equation 1.

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \quad \text{.............(1)}$$

$$v_m = 8.76\, m/s$$

   Standard Deviation: As a statistical measure, the standard deviation of wind speed indicates the dispersion or variability of wind velocities relative to their mean value. It gives data regarding the extent to which the actual wind speeds differ from the mean or average wind speed. A larger degree of variability in wind speeds is indicated by a higher standard deviation, whereas wind conditions that are more consistent are suggested by a lower standard deviation. The standard deviation can be found by equation 02:

$$\sigma_V = \sqrt{\frac{\sum_{i=1}^{n}(v_i - v_m)^2}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$\sigma_V = 4.62\ m/s$$

Normally this can be found using excel standard function.

2. Finding K and C value of Weibull distribution. Empirical method to find K and C using equation 1 and 2:

   Weibull distribution: A specific instance of the Pierson class III distribution is the Weibull distribution. The probability density function(equation 5) and the cumulative distribution function(equation 6), in the Weibull distribution, are the two functions that describe the fluctuations in wind velocity. The probability density function f (V) shows the probability (or fraction of time) that the wind will be at a specific velocity V. Cumulative distribution function of the velocity V gives us the fraction of time (or probability) that the wind velocity is equal or lower than V.

3. k is the Weibull shape factor and c is scale factor . Empirical method to find K and C using equation 3 and 4:

$$K = (\frac{\sigma_v}{V_m})^{-1.09} \quad \ldots\ldots\ldots\ldots..(3)$$

$$K = (\frac{4.62}{8.76})^{-1.09}$$

$$= 2.006$$

$$c = \frac{2V_m}{\sqrt{\pi}} \quad \ldots\ldots\ldots\ldots\ldots.(4)$$

$$c = \frac{2 \times 8.76}{\sqrt{\pi}}$$

$$= 9.89$$

Step 3: Estimate the wind resource potential:

1. Finding Probability distributions and cumulative distribution function of wind using equation 5 and 6(Appendix A) :

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1}e^{-\left(\frac{v}{c}\right)k} \text{ ....}\textbf{(5)}$$

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)k} \text{ ....}\textbf{(6)}$$

2. **Finding Energy density using equation 5.** An essential first step in the planning of a wind energy project is assessing the energy available at a given site under the dominant wind regime. Two primary criteria are usually used to evaluate the energy potential: wind energy density and the amount of energy accessible within the regime during a specified time frame. The quantity of energy available within the regime per unit rotor area and time is known as wind energy density, or E_D. As a result, E_D depends on the regime's wind dispersion and velocity.

$$E_D = \frac{\rho_a c^3}{2}\frac{3}{k}\Gamma(\frac{3}{k}) \text{ ....}\textbf{(7)}$$

=794.7835 KW/m²

$\boldsymbol{P_a}$ =Air density

3. The most frequent wind velocity at the site is given by equation 6. The probability density function can identify the most frequent wind velocity, which corresponds to the peak of the distribution curve.

$$v_{Fmax} = c(\frac{k-1}{k})^{\frac{1}{k}} \text{..............}\textbf{(8)}$$

=7.01 m/s

4. The most energy carrying wind speed is given by equation 7. The wind speed at which the wind energy density is highest indicates the optimal wind speed for energy generation.

$$v_{Emax} = c(\frac{k+2}{k})^{\frac{1}{k}} \text{..............}\textbf{(7)}$$

=13.96 m/s

Step 4: Get the power curve of 5 wind turbines with 3 MW range:

1. We will evaluate 5 different wind turbines for the prospective site. The links for the 5 sites are given at Appendix B.

2. To take the necessary information for the 5 curves are taken through a excel sheet. The link of this sheet is given appendix C. The necessary information that should be taken out are:
   a) **Cut In speed:** The term "cut-in speed" relates to the the minimum wind velocity at which the power-generating blades of a wind turbine begin rotation. It denotes the point at which the turbine initiates the generation of electrical energy. Between 6 and 9 mph (miles per hour) or 2.7 and 4 m/s (metres per second) is the typical cut-in speed[7].
   b) **Cut out speed:** The term "cut-out speed" pertains to the highest wind velocity at which the turbine must be stopped in order to prevent any potential harm. The turbine's control system initiates a shutdown mechanism when wind speeds surpass the cut-out speed, safeguarding the machinery from undue stress and possible malfunction. The exact cut-out speed may differ based on the wind turbine's design and specifications. The manufacturer determines this parameter throughout the design and construction phases of the turbine.

   c) **Rated speed:** The wind turbine's "rated speed" is the speed at which it begins to generate its rated power. During the turbine's design and building phases, the manufacturer sets this parameter.

   d) **Rated Power:** The most energy that a wind turbine is capable of producing is known as its rated power. Usually, the rated speed—the wind speed at which the turbine generates its maximum power capacity—is when the rated power is attained.

The parameters of the wind turbine can be observed from figure 2 .

Step 5: Modeling power curve of 5 wind turbines using plot digitizer:

1. Using online WebPlot Digitizer to model the power curve of the turbines.

   Power Curve: The power curve of a wind turbine represents the relationship between the wind speed and the electrical power output it can generate[8]. It is a crucial characteristic that helps assess the performance and efficiency of a wind turbine. A typical power curve is presented at figure 2.

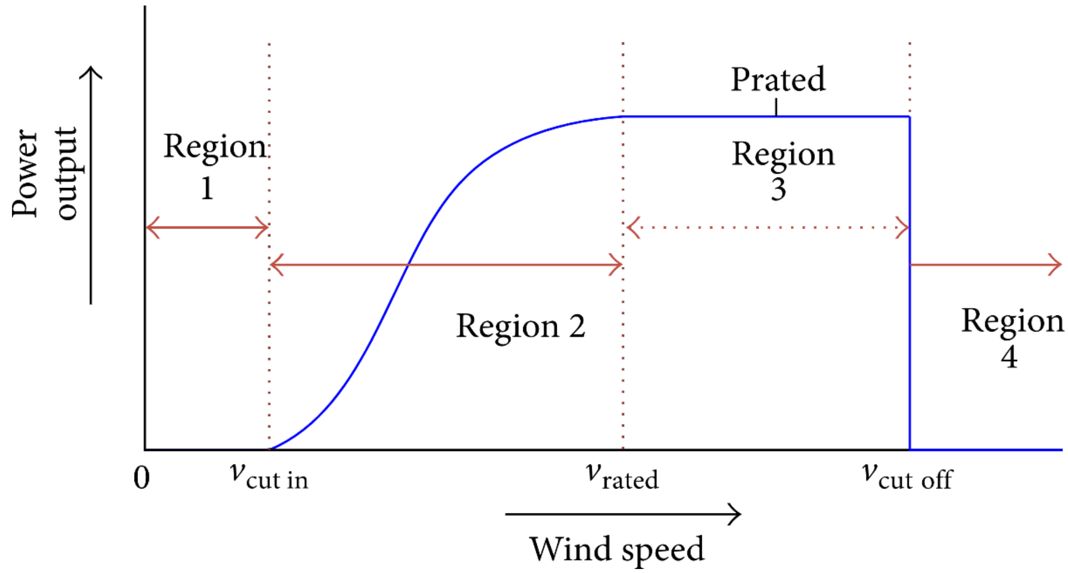

Fig.2. Power Curve of a wind turbine

2. Export the data into CSV file. In this case we will only take the values up to rated power so that we can interpolate it later. (Appendix C)
3. Interpolation of Power curve using interpolation method at Matlab (Appendix D)

   Interpolation: Interpolation is a technique for estimating values from a set of known data points. It involves forming educated assumptions about values that lie between certain data points based on the given data. Linear interpolation, for example, is a simple technique that uses a straight line to estimate values between two known data points. Polynomial interpolation fits the data points accurately with higher-degree polynomials, whereas spline interpolation creates a smooth curve over the data with piecewise functions. We will interpolate the data between the cut in speed and the rated speed to obtain some specific values within this range.

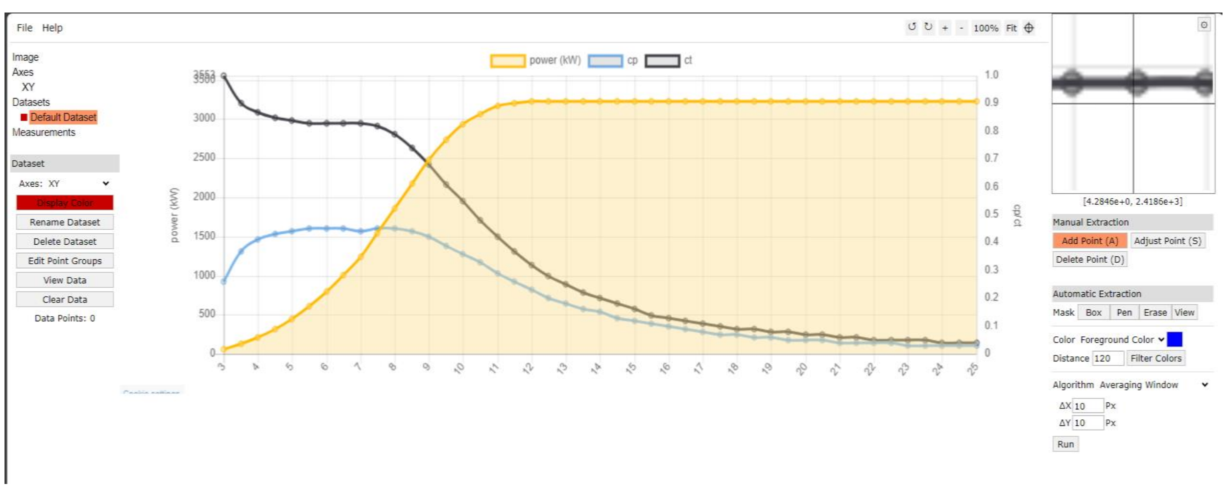

Fig.3. Online Webplot Digitizer

Step 6: Computation of Annual Energy Production using the WERA model :

1. Calculate the total energy production of each turbine using the following formulas. This can be done in Matlab(Appendix E).
   Basically, the power curve is divided into three region (Figure 2).

   <u>Region I, Stalled Power Region:</u> In this region the wind run don't start to run as the wind speed is below cut-in speed. So no power isa generated at this speed.

   <u>Region II, Dynamic Region:</u> The turbine operates below its rated power capacity in this region due to the low wind velocity. The goal is to harvest as much power as possible from the available wind by rapidly increasing the power output as the wind speed increases.

   E_{IR} total energy throughout a time T corresponding to the turbine's dynamic region.

   <u>Region III, Deterministic Region:</u> The turbine continues to function at its rated power output in this region, which has critical wind speeds. The power output, however, may be reduced or managed to avoid excessive strain on the turbine and for safe operation.

   E_{RO} total energy corresponding to deterministic region of the turbine over a time T.

   E_T total energy developed by the turbine over a time T.

$$E_{IR} = T \int_{V_i}^{V_R} P(V) f(V) dV$$

$$E_{Ro} = T \int_{V_R}^{Vo} P_R f(V) dV$$

Total Energy: $E_T = E_{Ro} + E_{IR}$

Here:

T= Time

$P(V)$=Power Curve equation of turbine

$f(V)$ = Probability distributions of wind

P_R= Rated Power

V_R= Rated Speed

V_i =Cut in Speed

Vo= Cut out Speed

Step 7: Computation and Comparison the capacity factor of the turbines at the site:

1. A wind turbine's capacity factor (CF) at a specific location is the ratio of the energy that the system actually produces to the amount of energy that it could have produced if it had run at its rated power throughout the duration of the measurement. Compute the capacity factor by the following equation and make a comparison among the turbines. Typical capacity factors for current wind farms range between 25% and 45%.

$$C_F = \frac{E_T}{TP_R}$$

Flow chart of the whole methodology is presented by the figure 4:

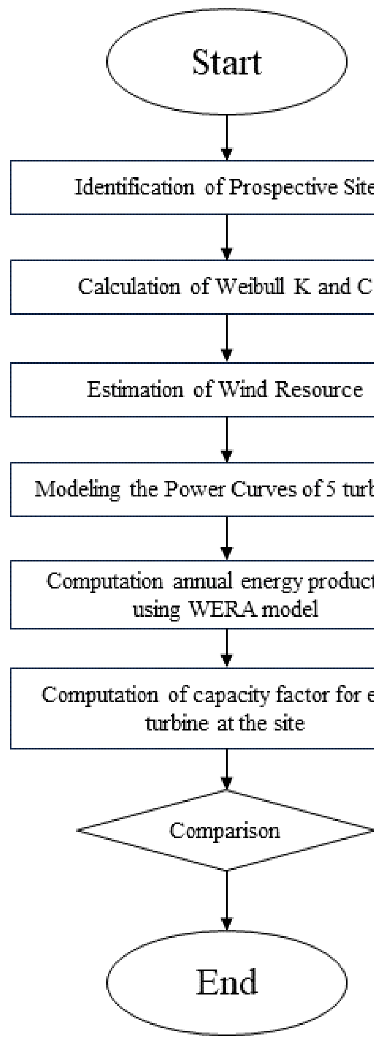

Figure 4: Flow Chart of the methodology

Results

In this section we will present the characteristics of 5 different wind turbine and their corresponding energy density and capacity factor at the prospective site. Here the method that has been described in the methodology section will be used.

Table 1: Characteristics of 5 different turbines

SL	Turbine Name	Cut In speed(m/s)	Cut Out Speed(m/s)	Rated Speed(m/s)	Rated Power (KW)
1	GE General Electric 3.2	3	25	12	3200
2	Enercon E-82 E4 3.0	3	25	16	3000
3	Gamesa G132-3.3	3	25	11	3300
4	Suzlon S133 2.6 to 3	3	20	9	2600
		3	20	10	3000
5	Nordex N131/3000 Delta	3	20	11	3000

At table 2 a comparison of Energy produced and Capacity factor among the turbines have been presented.

Table II: Comparison of performances among the turbines

SL	Turbine Name	E_{IR} (KWh)	E_{OR} (KWh)	E_T (KWh)	Capacity Factor
1	GE General Electric 3.2	3.73e6	3.41e6	7.14e6	27.20%
2	Enercon E-82 E4 3.0	3.42e6	1.67e6	5.10e6	19.41%
3	Gamesa G132-3.3	3.52e6	8.38e6	7.51e6	25.98%
4	Suzlon S133 2.6 to 3	1.71e6	4.18e6	5.9e6	25.9%
		3.93e6	4.08e6	8.02	30.51%
5	Nordex N131/3000 Delta	3.07e6	3.46e6	6.58e6	24.88%

Conclusions

When the capacity factor of a given wind turbine is greater than the capacity factor of other turbines at a site, it means that the specific turbine generates a higher percentage of its maximum power production than the other turbines at that location. So for this site **Suzlon S133 2.6 to 3 and GE General Electric 3.2** type turbine will be more suitable than others. We will get maximum amount of power if we use these two types at the prospective site. Also, as the capacity factor for the most of the turbines in is in the range of 20%-30% so we can also say that our selected is quite perfect for harnessing wind energy.

So we got plenty of information out of this study since we learnt how to compare wind energy futures on a prospective site. We also learned about the criteria involved in site selection and the selection of a suitable turbine for that specific site. The first stage is to carefully pick a suitable location for the creation of a wind project. Typically, the site is chosen based on characteristics such as geographical position, wind resource availability, and topography and environmental issues. However, for the sake of simplicity in this project, we will choose a site at random and focus on wind velocities greater than 100 meters above ground level. Wind farms are subject to natural wind variability, which can result in a haphazard pattern of power variation. As a result, the turbine with the highest capacity factor should be chosen. This work will allow us to explore any potential future plans for capturing wind energy from a specific location.

References

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Appendix A

Historical Data of Prospective Site:

wind_data.xlsx

Appendix B

GE General Electric GE 3.2-130:

GE General Electric GE 3.2-130 - 3,20 MW - Wind turbine (wind-turbine-models.com)

Enercon E-82 E4 3.000:

Enercon E-82 E4 3.000 - 3,00 MW - Wind turbine (wind-turbine-models.com)

Gamesa G132-3.3MW:

Gamesa G132-3.3MW - 3,30 MW - Wind turbine (wind-turbine-models.com)

Suzlon S133 2.6 to 3 MW Platform

S 133 Wind Turbine Generator | Suzlon Energy LTD

Nordex N131/3000 Delta

Nordex N131/3000 Delta - 3,00 MW - Wind turbine (wind-turbine-models.com)

Appendix C

Power Curves of 5 wind turbines

Powee_Curves.xlsx

Appendix D

Interpolation:

```
clc
clear all
close all
%put the data of wind speed and power that has to be interpolated

x=[x1,x2,...]; %wind Speed
y=[y1,y2,...]; %power

% Step 2: Plot the data
figure;
plot(x, y, 'o', 'MarkerSize', 10); % 'o' for markers, you can change it as needed
title('Original Data');
xlabel('X');
ylabel('Y');

% Step 3: Interpolate to get more points
x_interp = linspace(3, 11, 9)% Create 9 equally spaced points for interpolation
y_interp = interp1(x, y, x_interp, 'spline') % 'spline' for cubic spline interpolation

% Step 4: Plot the interpolated curve
figure;
plot(x, y, 'o', 'MarkerSize', 10, 'DisplayName', 'Original Data');
hold on;
plot(x_interp, y_interp, 'r-', 'DisplayName', 'Interpolated Curve');
title('Interpolated Curve');
xlabel('X');
ylabel('Y');
legend;

% If you want to save the interpolated data to variables, you can use x_interp and y_interp.
```

Appendix E

Annual Energy Production and Capacity Factor using WERA model:

```
clc
clear all
% Define the sets of f1(X) and f2(X) values
f1 =[f11,f12,...];  % Corresponding to f(V)
values
f2 =[f21,f22,....];  % Corresponding to P(V) values from interpolation

% Define the x values(wind speed) corresponding to f1(X), f2(X)
x_values = [3 4 5 6 7 8 9 10 11 12 13 14 15 ];

% Check if the number of elements in f1 and f2 match
if length(f1) == length(f2)
   % Multiply the corresponding values of f1 and f2
   product = f1 .* f2;

   % Integrate the product using the trapezoidal rule
```

```
    result = trapz(x_values, product) *8760;

    fprintf('The result of the integration is: %.4f\n', result);
else
    disp('The number of elements in f1 and f2 do not match.');
end


f11 = [3000 3000 3000 ....];  % Rated Power
f22 = [f221 f222 ..];  % Corresponding to f(v) values

% Define the x1 values(wind speed) corresponding to f11(X), f22(X)
x1_values = [16 17       18       19       20       21       22       23       24       25];

% Check if the number of elements in 11 and f22 match
if length(f11) == length(f22)
    % Multiply the corresponding values of f11 and f22
    product = f11 .* f22;

    % Integrate the product using the trapezoidal rule
    result1 = trapz(x1_values, product) *8760;

    fprintf('The result of the integration 2 is: %.4f\n', result1);
else
    disp('The number of elements in f11 and f22 do not match.');
end

total_power=(result+result1)

capacity_facotr=(total_power)/(8760*3000)
```