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Research Article

Build-up an analysis model to evaluate wind potential for selecting suitable turbine configurations and proposing research to optimize wind farm design

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ABSTRACT

Before a wind farm is constructed, the assessment of wind potential in the proposed turbine installation area must be carried out as a prerequisite. To achieve the highest efficiency, the key concepts and a deep understanding of wind energy evaluation must be mastered by the design engineers. The article of study applies Weibull distribution theory and aerodynamics fundamental to build an analytical model for evaluating standards and estimating annual electricity output based on raw input data collected over a year. The calculation results for the wind characteristics, including shape and scale factor and power density at the surveyed area corresponding to an 80m height, are determined in detail by simulation software. The analysis results also indicate that the wind potential here is classified as very high (class 6), and a minimum II-A type turbine configuration must be selected to withstand these wind conditions.

Since the initial investment cost of a wind farm will be determined by the simulation results, the study aims to combine the calculation methods used in this research with the application of digital twin solutions and machine learning for wind farms to create an accurately digital replica of a physical system. In this way, real-time system operations will be monitored and continuously updated into the simulation model to understand and predict its behavior. From there, optimal design and operation adjustments will be made to enhance the overall system's efficiency and minimize errors and risks for investors.

Key words: Wind potential assessment analysis, digital twin application, machine learning technology in wind power in Vietnam.

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INTRODUCTION

Recently, within the national strategy on Climate Change, the Vietnamese government has announced the goal of reducing emissions by 43.5% by 2030, with practical proposal and effective international support. Emission targets have been set for each sector for the years 2030 and 2050, alongside several qualitative proposals to achieve these goals. Among these proposals are policies to support the development of wind power projects in Vietnam [13].

To construct a wind power plant, the first requirement is to have a basic knowledge of wind energy. Specifically, whether a wind power project is grid-connected or standalone, the core activity to assess the feasibility of the project is the Wind Resource Assessment (WRA) process [9]. The output data from WRA will be used and serve as the input for financial analysis and the overall feasibility assessment of entire project [10].

Currently, wind farms are increasingly being developed, offering significant opportunities to enhance autonomous operation and optimize system productivity. In light of these, the research has developed an annual energy production (AEP) analysis model to select suitable turbine configurations [2].

This analytical model plays a vital role in providing estimated electricity generation results with high reliability and accuracy of 100% when the characteristic parameters of the input wind dataset are identified. Additionally, the model also assists in predicting energy sources at different altitudes when planning designs to aid in feasibility assessments. The research results will provide a more detailed and intuitive perspective on providing useful scientific information that serves as a valuable reference for future wind power projects.

INPUT DATA AND METHODOLOGY

Data source

The input data consist of wind speed measurements taken every 10 minutes continuously over one year at the Con Dao telecommunications station as in Figure 1 at altitudes of 30m, 50m, and 60m above ground level respectively.

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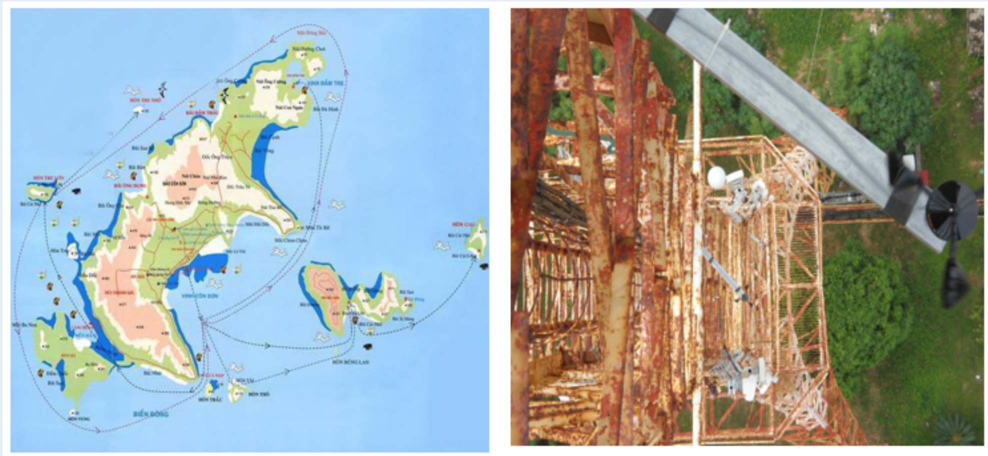

Figure 1: The Con Dao Island map and picture of installation of anemometer at altitudes of60m, 50m & 30m

Based on these gathered wind speed data series, which to be presented in the form of Table 1 and chart as shown in Figure 2 to analyze and evaluate the characteristic of the avarage hourly wind speed at diffferent elevation.

Methodology

In this study, an experimental method is proposed by collecting and processing data along with a mathematical method of probabilistic statistical analysis. According to the Weibull distribution is used to determine the importantly characteristic parameters of wind. Thermodynamic properties of moist air also is applied to build a simulation model by using MATLAB software to provide predictive results and potential assessment.

The classification of turbines according to the IEC-1400-1 standard is determined by average wind speed and turbulence intensity. The IEC-1400-1 standard defines four standard classes: I, II, III, IV, and an additional class S. For class S, all wind field parameters must be specified by the manufacturer. The average wind speeds for classes I through IV correspond to 10 m/s, 8.5 m/s, 7.5 m/s, and 6 m/s, respectively. In addition to these standard classes, turbulence intensity is categorized into high, medium, and low (classes A, B, and C).

THE ANALYSIS MODEL FOR EVALUATION AND ESTIMATING ANNUAL ELECTRICITY OUTPUT

The kinetic energy (E) of the wind in moving can be determined as the formular [5]

$E = \frac{1}{2}mv^2\ (joules)$ (3-1)

where m is the mass of air passing through a circular plane perpendicular to the wind direction and v is the mean wind speed over a suitable time period that can be seen in Figure 3 .

The wind power can be obtained by differentiating the kinetic energy in wind with respect to time:

$$P = \frac{dE}{dt} = \frac{1}{2}\dot{m}v^2 \qquad (3\text{-}2)$$

However, only a small portion of wind power can be converted into electrical power. When wind passes through a wind turbine and drives blades to rotate, the corresponding wind mass flowrate is:

$$\dot{m} = \rho A v \qquad (3\text{-}3)$$

Where ρ is density of a moist air (kg/m^3) and A is the swept area of blades (m^2)

From above formula of (3-2) and (3-3), simplifying this we get a power (P) can be expressed as [5] :

$$P = \frac{1}{2}\rho A v^3 \quad (watts) \qquad (3\text{-}4)$$

The effective power through a wind turbine for electricity generation is significantly less than the energy in the air stream. According to Betz's law, theoretically, only a maximum of 59,3% of the energy in the air stream can be captured because the wind speed behind a turbine cannot be fully absorbed and reduced to zero.

Statistical modeling of wind speed data

The statistical modeling method is applied the Weibull probability distribution as a crucial form to describe the statistical appearance of extreme values

Table 1: Hourly average wind speed at different elevation

Hour	Wind speed (hourly average), m/s		
	60m (Channel 1)	50m (Channel 2)	30m (Channel 3)
0	6.32	5.68	4.18
1	6.14	5.51	4.07
2	6.10	5.47	4.05
3	6.25	5.60	4.14
4	6.32	5.66	4.19
5	6.52	5.85	4.34
6	6.60	5.92	4.37
7	6.77	6.07	4.49
8	7.03	6.30	4.67
9	7.23	6.49	4.82
10	7.45	6.68	4.93
11	7.61	6.83	5.05
12	7.72	6.92	5.11
13	7.90	7.08	5.21
14	8.03	7.20	5.33
15	8.13	7.29	5.40
16	8.07	7.23	5.35
17	7.95	7.13	5.25
18	7.84	7.04	5.20
19	7.62	6.83	5.06
20	7.29	6.54	4.85
21	7.02	6.30	4.66
22	6.73	6.03	4.45
23	6.55	5.87	4.34
Average	7.13	6.40	4.73

in meteorology, hydrology and weather forecasting. The Weibull distribution provides a reasonable mathematical description for wind speed graphs. This distributon is used to analyze probability, predict operational time, and estimate the electricity generation.

The Weibull probability density function :

$$pd(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} exp\left(-\left(\frac{v}{A}\right)^{k}\right),\ (v > 0) \quad (3\text{-}5)$$

Where:

k: Shape factor

A: Scale factor

Below frequency distribution graphs are created by grouping wind speeds. The shape parameter k and the scale parameter A allow the Weibull function to be fitted to the measured frequency distributions. Each region will have different k and A values, as illustrated in Figures 4 and 5 .

Power density of wind speed

To understand the inpact of the statistical distribution of wind speed on power generation, we need to calculate this power density of wind speed.

Power density (PD) is defined as follow:

$$PD = \frac{Power}{Swept\ area} = \frac{1}{2}\rho v^3 \quad \left(\frac{W}{m^2}\right) \quad (3\text{-}6)$$

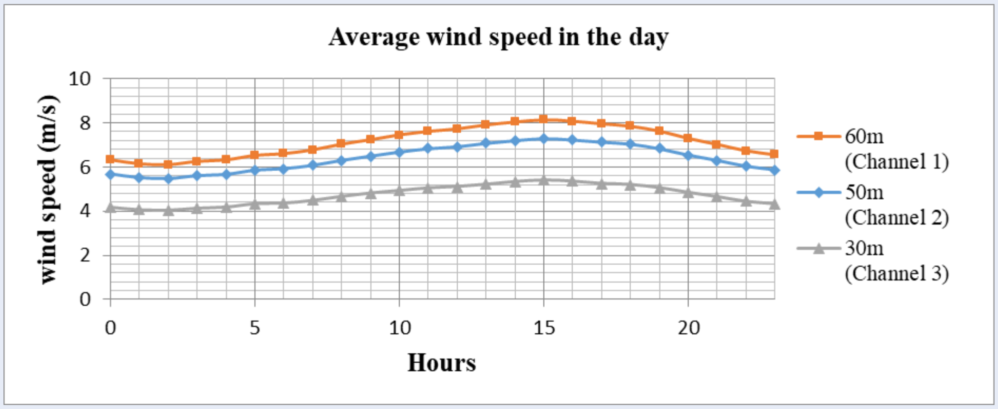

Figure 2: Hourly average wind speed in year (from 0h to 23h) at observed heights.

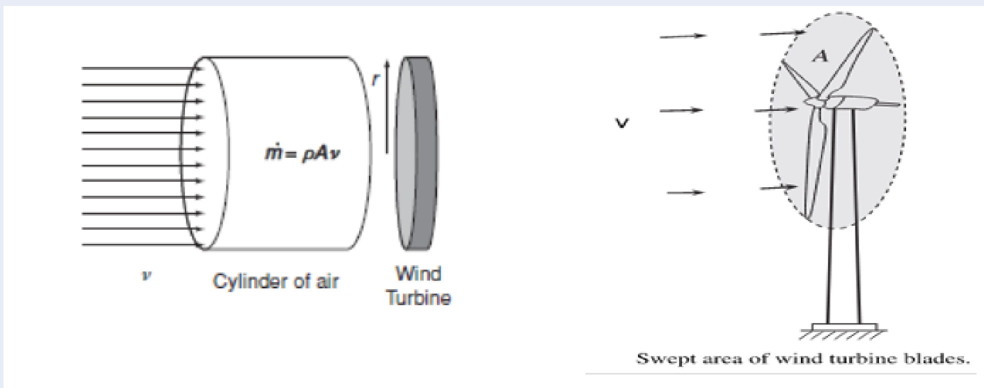

Figure 3: Kinetic energy and swept area of wind turbine

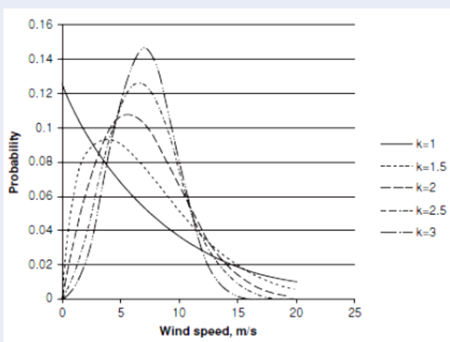

Figure 4: Weibull probability density function according to k-values

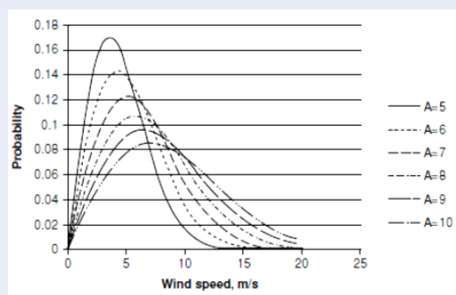

Figure 5: Weibull probability density function according to A-values

However, this PD value must be applied integral function to achieve result more accurate:

$$Correct\ PD = \int_0^{\infty} \frac{1}{2} \rho v^3 pd(v)\, dv \quad \left(\frac{W}{m^2}\right) \qquad (3\text{-}7)$$

Where: v is wind speed (m/s), pd(v) is Weibull probability density function

Conventionally, wind intensity in the surveyed area is classified based on power density to evaluate the wind energy potential of that specific area. To assess this

Table 2: Wind classification at reference heights 10m & 50m [1]

Wind Class	Category	10m		50m	
		Power density W/m2	Average velocity m/s	Power density W/m2	Average velocity m/s
1	Poor	0-100	0-4.4	0-200	0.0-5.6
2	Marginal	100-150	4.4-5.1	200-300	5.6-6.4
3	Fair	150-200	5.1-5.6	300-400	6.4-7.0
4	Good	200-250	5.6-6.0	400-500	7.0-7.5
5	Excellent	250-300	6.0-6.4	500-600	7.5-8.0
6	Outstanding	300-400	6.4-7.0	600-800	8.0-8.8
7	Superb	400-1000	7.0-9.4	800-2000	8.8-11.9

potential, wind speeds are categorized into 7 levels according to Table 2 . Based on the calculated power density using formula 3-6, we can determine whether that area has wind potential or not.

Air density correction according to ambient temperature

Typically, wind energy is surveyed at ambient temperature. Air density (ρ) is also a factor that affects power density (PD). The relationship between PD and ρ is linear. Air density depends on pressure, temperature and relative humidity, both pressure and temperature decrease with altitude. The formula for calculating air density is obeyed the perfect gas equation of state as follows [3] :

$$pV = nRT \qquad (3\text{-}8)$$

Where:

- p: atmospheric pressure, (atm)
- V: total mixture volume (i.e dry air & water vapor), (m^3)
- n: number of moles of air (mol)
- R: universal gas constant, 8,314 J/(mol.K)
- T: absolute temperature, (K)

With ρ = n/V, molecular weight per volume unit.

$$\rho = \frac{p}{RT} \qquad (3\text{-}9)$$

Hence, the term M (gam) represents the molecular weight of air. Air density is defined in below formula:

$$\rho = \frac{p}{RT}\frac{M}{1000}\left(kg/m^3\right) \qquad (3\text{-}10)$$

Otherwise, the pressure depends on altitude. The pressure value may be calculated from [4,5] :

$$p = 101.325(1 - 2.25577 \times 10^{-5}Z)^{5.2559}\ (kPa) \quad (3\text{-}11)$$

Where:

M: the molecular weight of air, (M = 28.97 g/mol)

Z: altitude, m

This correction is necessary for wind energy assessment at different altitudes.

Wind speed distribution by Altitude

Wind speed is typically measured at a specific altitude above the sea level as indicated in Figure 6 . However, to enhance the efficiency of wind energy utilization, it is sometimes necessary to consider wind speeds at various heights. The equation for velocity as a function of altitude is expressed by the formula:

$$v_2 = v_1 \times \left(\frac{h_2}{h_1}\right)^{\gamma} \qquad (3\text{-}12)$$

Where:

v_1,v_2 is the wind speed at height h_1, h_2, respectively

γ is the wind shear exponent, which varies depending on the terrain and atmospheric conditions.

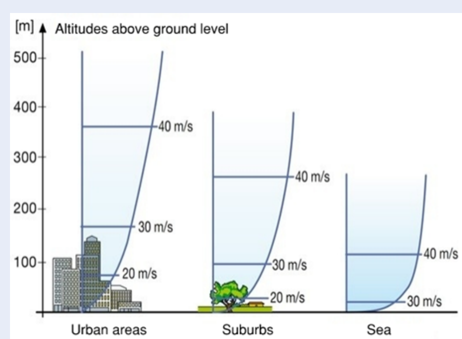

Figure 6: Wind speed distribution by height

In case of considering to extrapolate wind speed, γ-coefficient may be determined as follows:

$$\gamma = \frac{log\frac{v_2}{v_1}}{log\frac{h_2}{h_1}} \tag{3-13}$$

Additionally, in cases of lacking observational input data, we can refer to the Table 3 to find γ coefficient for each specific condition.

Correlation between characteristic parameters of the Weibull

In addition to the two characteristic parameters k and A factor of Weibull distribution. We may establish other relationship of wind speed as follow:

$$Mode = A\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{3-14}$$

$$Mean\ velocity = \bar{v} = A\Gamma\left(1+\frac{1}{k}\right) \tag{3-15}$$

$$Variance = \sigma^2 = \bar{v}^2\left[\frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)}-1\right] \tag{3-16}$$

Where: $\Gamma(x)$ is gamma function, if x is an integer then $\Gamma(x) = x!$

To simplify this, we may apply the approximate formula as below:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{3-17}$$

$$A = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{3-18}$$

ANALYTICAL RESULT OF WIND POTENTIAL ASSESSMENT AND TURBINE CONFIGURATION SELECTION

Frequency of wind speed levels

Wind speed data for determining frequency of occurrence

Based on the collected wind data series, the wind data will be summarized in a chart that shows the frequency of occurrence corresponding to speeds ranging from less than 1m/s to 25m/s at a typical height of 60m (see Figure 7).

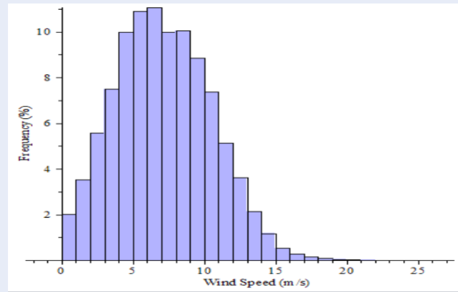

Figure 7: The statistical frequency of actual wind speed at the height of 60m

The analysis and observations of the wind speed frequency

- The frequency of wind speeds from 6m/s and above accounts for 60,5%.
- The maximum observed wind speed is 31,59m/s (recorded from the max channel of anemometer).

Statistical characteristics of the data series for

Data for determining statistical characteristics

Based on the 10 minute average wind speed data series, the statistical characteristics of the observed wind data will be calculated by using the Weibull distribution function. Applying the formulas to calculate k, A and PD. The results in Figure 8 at a height of 60m are as follows:

- Air density at 60m:
- Shape factor: k = 2,23
- Scale factor: A = 8,03
- Average wind speed: 7,12 m/s
- Mode = 6.17 m/s
- Standard deviation: σ = 3.36 m/s
- Power density: PD = 363,15 W/m^2

Analysis and Observation

With an average power density of approximately 363,15 W/m^2 at 60m, according to the Table 2 then the wind potential of this area is classified into class 3 which is very suitable for energy exploitation. When a wind turbine is installed at a height of 80m, its potential will be even better.

Table 3: Terrain's roughness classification & wind shear coefficient

Terrain Description	Roughness Class	Roughness length, m	Wind Shear Coefficient , γ
Offshore sea	0	0.0001 – 0.003	0.08
Open terrain, smooth surface (concrete roads, short grass)	0.5	0.0024	0.11
Agricultural land without obstacles, sparse buildings, or a few hills	1	0.03	0.15
Agricultural land with few houses and tree fences 8m tall spaced 1250m apart	1.5	0.055	0.17
Agricultural land with few houses and tree fences 8m tall spaced 500m apart	2	0.1	0.19
Agricultural land with few houses and tree fences 8m tall spaced 250m apart	2.5	0.2	0.21
Villages, small towns, agricultural land with many tall trees, rough terrain	3	0.4	0.25
Large cities with many high-rise buildings	3.5	0.8	0.31
Large cities with many skyscrapers	4	1.6	0.39

Source: Niesel, Per. WindPRO 2.5 Users Guide. EMDInternational, Aalborg, Denmark 2006.

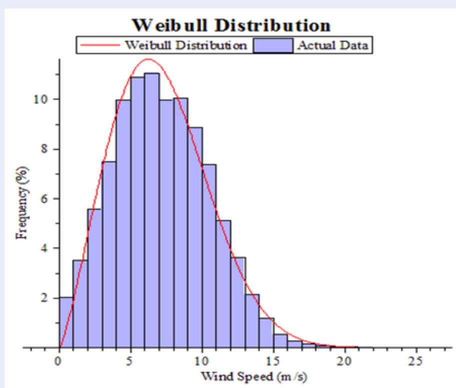

Figure 8: Characteristics of actual wind speed data at 60m follow Weibull Distribution

Wind Speed Data Conversion

Since the statistical data series of wind speed is not available at 80m, it is necessary to extrapolate and convert from the surveyed data series at other heights. Based on the collected data series, applying formula 3-13 to find out γ value which allows for the conversion of wind speed. To verify the accuracy of γ-coefficient, the statistical data series at a height of 60m is used to convert wind speeds at 30m and 50m respectively. These converted data are then compared and evaluated against actual data at these heights to conclude the reasonableness of the chosen γ value. Using this method, the converted and statistical data values are listed in Table 4 and illustrated in Figure 9

As the result inTable 4 and Figure 9 , the error between the calculated converted data and actual collected data is negligible and entirely acceptable. All curve lines representing these data are almost coincident.

Conclusion: Using the formula to calculate γ-coefficient for converting wind speed at a height of 80m is accepted.

Variation of Average Hourly Wind Speed Throughout the Year at 80m Height

Characteristic Parameters of the Data Series for Calculation

Based on the 10-minute average wind speed data series collected at heights of 30m, 50m, and 60m, the extrapolation of wind data to a height of 80m was carried out as indicated in Table 5 and Figure 10). The wind data characteristics were derived using the Weibull distribution function, similar to the method used for the 60m height. The results are illustrated in Figure 11 and Figure 12 .

Where:

- Air density at 80m: ρ = 1,167 kg/m3
- Shape factor: k = 2,23
- Scale factor: A = 9,55
- Average wind speed: 8,46 m/s
- Mode = 7.32 m/s

Table 4: Average hourly windspeeds throughout the Year at observed heights of the statistical data seriesand calculated converted data

Hour	Actual data series			Converted data according to heights				**Wind Shear** γ
	60m (Channel 1)	50m (Channel 2)	30m (Channel 3)	80m	60m	50m	30m	
0	6.32	5.68	4.18	7.52	6.32	5.67	4.18	0.601
1	6.14	5.51	4.07	7.30	6.14	5.51	4.07	0.599
2	6.10	5.47	4.05	7.25	6.10	5.47	4.04	0.597
3	6.25	5.60	4.14	7.44	6.25	5.60	4.13	0.603
4	6.52	5.66	4.19	7.52	6.32	5.66	4.17	0.603
5	6.52	5.85	4.34	7.75	6.52	5.85	4.32	0.598
6	6.60	5.92	4.37	7.85	6.60	5.92	4.36	0.600
7	6.77	6.07	4.49	8.05	6.77	6.07	4.48	0.601
8	7.03	6.30	4.67	8.35	7.03	6.30	4.65	0.599
9	7.23	6.49	4.82	8.59	7.23	6.49	4.79	0.597
10	7.45	6.68	4.93	8.87	7.45	6.68	4.92	0.603
11	7.61	6.83	5.05	9.05	7.61	6.83	5.04	0.599
12	7.72	6.92	5.11	9.19	7.72	6.92	5.10	0.600
13	7.90	7.08	5.21	9.40	7.90	7.08	5.21	0.604
14	8.03	7.20	5.33	9.56	8.03	7.20	5.30	0.602
15	8.13	7.29	5.40	9.66	8.13	7.29	5.38	0.598
16	8.07	7.23	5.35	9.60	8.07	7.23	5.33	0.603
17	7.95	7.13	5.25	9.47	7.95	7.12	5.25	0.601
18	7.84	7.04	5.20	9.32	7.84	7.04	5.20	0.599
19	7.62	6.83	5.06	9.05	7.62	6.83	5.04	0.601
20	7.29	6.54	4.85	8.66	7.29	6.54	4.83	0.597
21	7.02	6.30	4.66	8.35	7.02	6.30	4.65	0.600
22	6.73	6.03	4.45	8.00	6.73	6.03	4.45	0.599
23	6.55	5.87	4.34	7.78	6.55	5.87	4.33	0.599
Mean	**7.13**	**6.40**	**4.73**	**8.48**	**7.13**	**6.40**	**4.72**	**0.60**

- Standard deviation: σ = 4.0 m/s
- Power density: PD = 608,29 W/m2

Observation:

With an average power density of approximately 608.29 W/m^2 at a height of 80 meters, the wind potential of this area is very high and classified into class 6. Comparing the results at heights of 60m and 80m, it is evident that the higher the altitude, the greater the energy potential. Therefore, installing wind turbine at a height of 80 meters is very reasonable.

Selection of Turbine Based on Power Generation Capacity and Annual Electricity Production Estimation

Selection of Power Generation Capacity

The selection of the wind turbine's power generation capacity should align with the load demand requirement. Refer to the hourly load demand Table 6 .

Where:

- Max load demand, Pmax = 4,580.48 kW

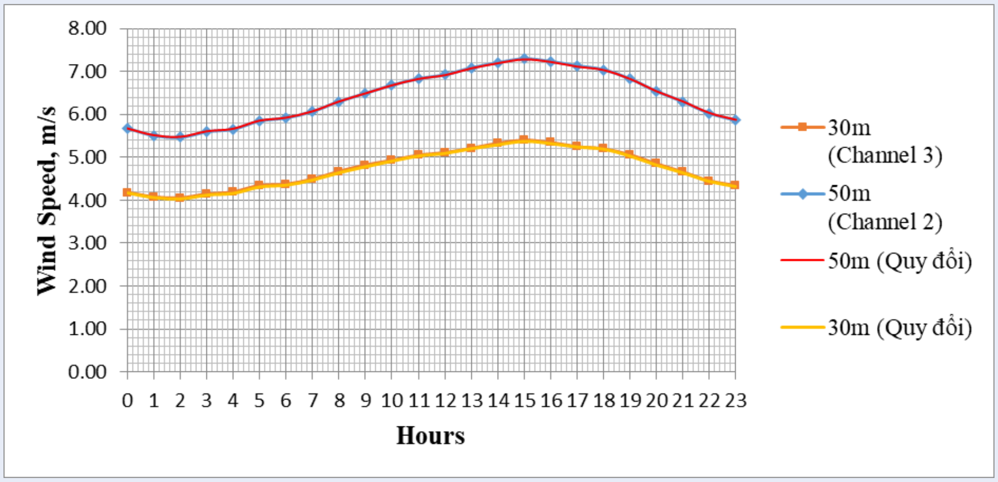

Figure 9: Average hourly wind speeds throughout the year at observed heights and converted

Table 5: Average Hourly Wind Speeds Throughout the Year at 80m Height, Extrapolated from the Statistical Data Series

Average Hourly Wind Speeds, m/s		Average Hourly Wind Speeds, m/s	
Hours	80m (Extrapolated)	Hours	80m (Extrapolated)
0	7.52	13	9.40
1	7.30	14	9.56
2	7.25	15	9.66
3	7.44	16	9.60
4	7.52	17	9.47
5	7.75	18	9.32
6	7.85	19	9.05
7	8.05	20	8.66
8	8.35	21	8.35
9	8.59	22	8.00
10	8.87	23	7.78
11	9.05	Average	8.48
12	9.19		

- Min load demand, Pmin = 2,479.26 kW
- Ave. load demand, Pave = 3,617.22 kW

From the Table 6 of given load data, to ensure a stable power supply for the island and minimizing dependence on the previous diesel system to reduce greenhouse gases, a turbine capacity should be selected greater than the peak load. Here, the total system capacity of 5MW is chose as shown in Figure 13 .

Basis for selecting wind turbine capacity:

- The selected turbine capacity must meet the load demand and ensure uniform distribution.
- The power penetration level from the wind power system must achieve at least 50%.
- It should align with the financial capacity of the investor.
- Under the same conditions, the harmonization between technical aspects and investment costs must be taken into account.

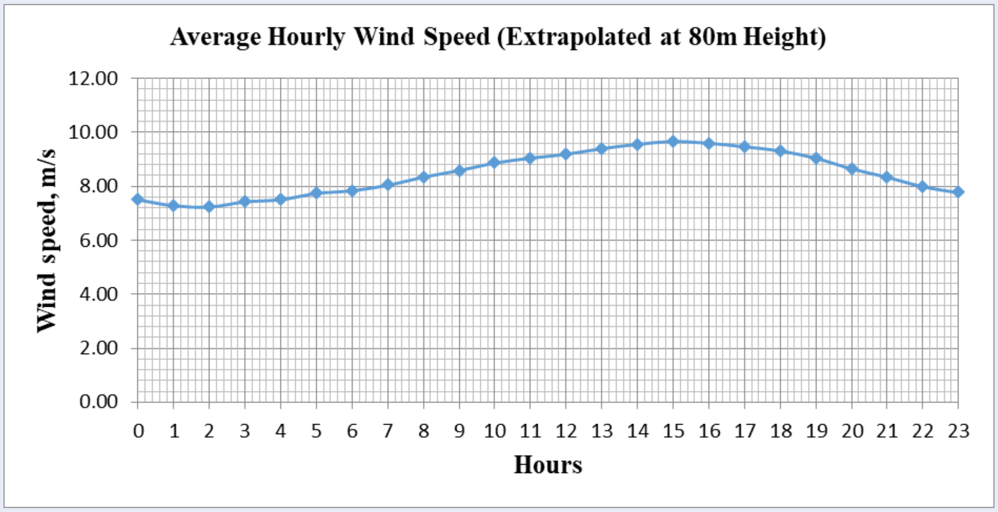

Figure 10: Average Hourly Wind Speeds Throughout the Year at 80m Height, Extrapolated from the Statistical Data Series

Table 6: Hourly Load DemandSummary at Con Dao Island

Hours	Load Demand, KW	Hours	Load Demand, KW
1	4,580.48	13	4,059.10
2	2,958.77	14	3,701.82
3	2,479.26	15	4,421.96
4	2,501.59	16	3,514.80
5	2,764.47	17	3,779.97
6	3,322.21	18	3,668.32
7	3,391.99	19	4,212.62
8	3,782.76	20	3,403.07
9	4,070.26	21	3,679.40
10	3,715.77	22	3,763.14
11	4,156.79	23	3,768.72
12	4,112.13	24	3,003.92

- A backup plan must be considered in case one of the devices needs maintenance or replacement.

Conclusion:

Above these criteria, the most suitable configuration is to choose 2 turbines with a capacity of 2.5 MW each, totalling 5 MW.

Estimation of Annual Electricity Production

Wind speed frequency simulation result

To accurately determine the number of hours per year that the wind speed reaches between v_1 and v_2, the following equation can be used

$$Number\ of\ hours\ per\ year\ (v_1 \leq v \leq v_2) = 8760 \int_{v_1}^{v_2} f(v)\, dv \quad (4\text{-}1)$$

Where:

8760: Total number of hours in a year.

f(v): The probability density function of wind speed

Based on the collected statistical data and the extrapolated wind speed results at a height of 80m, the parameters of Weibull distribution can be found:

- k = 2,23
- A = 9,55

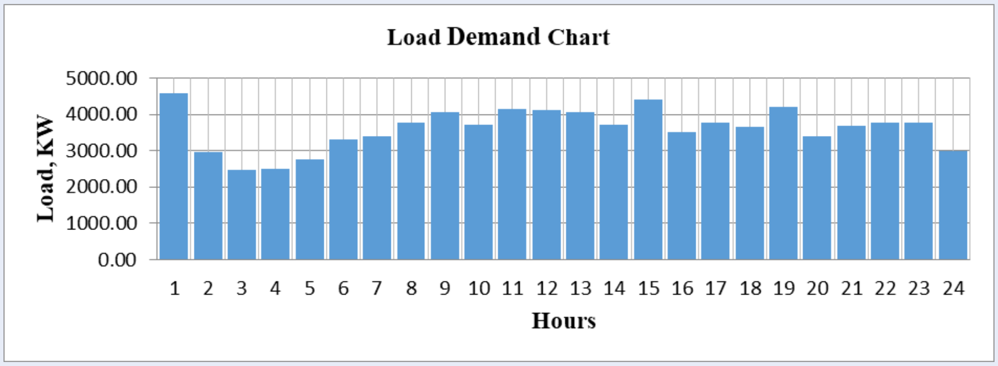

Figure 13: Hourly Load Demand Summary at Con Dao Island

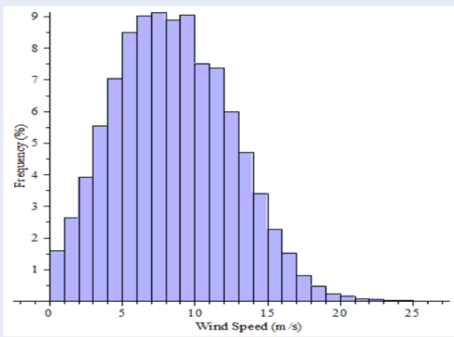

Figure 11: The statistical frequency of converted wind speed at the height of 80m

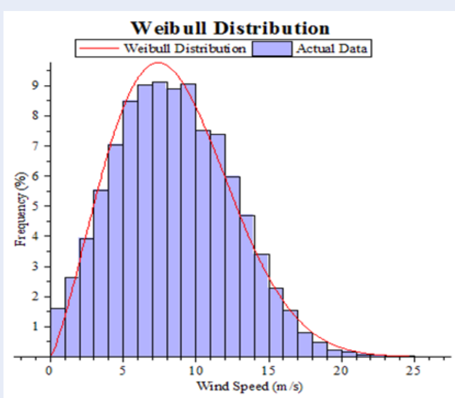

Figure 12: Characteristics of wind speed data at 80m follow Weibull Distribution

Applying the above formula with the determined values of k, A. The wind speed frequency tabulated in Table 7 and shown in Figure 14 .

Power Generation Characteristics of the Wind Turbine

For the selected wind turbine with a power capacity of 2.5MW, refer to the typical power output (P) of Enercon manufacturer [15] according as wind speed (v). The power curve of a turbine 2.5 MW is as Table 8 .

In the given Table 8 , the cut-in wind speed at which the wind turbine start operating is 2m/s, the power output of the wind turbine increases rapidly as the wind speed increases respectively. The turbine reaches its rated power and maintain as it at 12m/s. When the wind speed exceeds 25m/s, the wind turbine automatically activates its protection system for cut-out, ensuring the safety of the equipment (see Figure 15).

Estimation of annual electricity production

The annual electricity production of a wind turbine is the product of its power output (P) and the operating time in one year. From the statistical Table 9 , the annual electricity production can be estimated as Table 9 .

- As seen in Figure 16 , the annual electricity production from a 2.5 MW turbine produces approximately 12.644 million kWh/yr. Therefore, the total production from the system will be around 25.29 million kWh/yr.
- Maximum operating hours (Tmax) is 12.64 x10^6/2500 = 5057.41 hr/yr.

Calculation of Turbulence Intensity and

To select the appropriate wind turbine capacity for installation at a specific area, the turbulence intensity

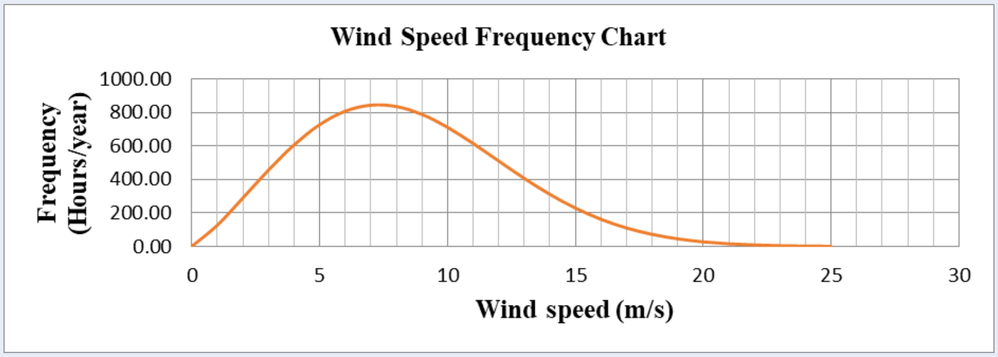

Figure 14: Occurrence wind speed frequency chart at 80m

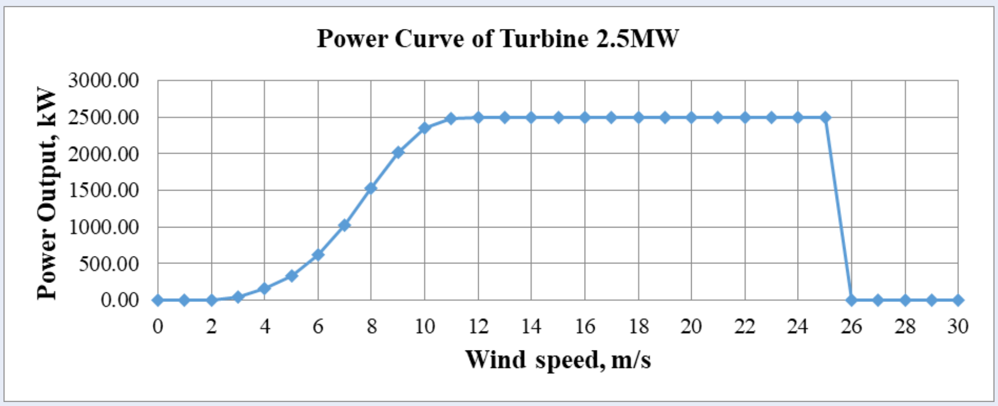

Figure 15: Power output characteristic curve of a typical turbine 2.5MW

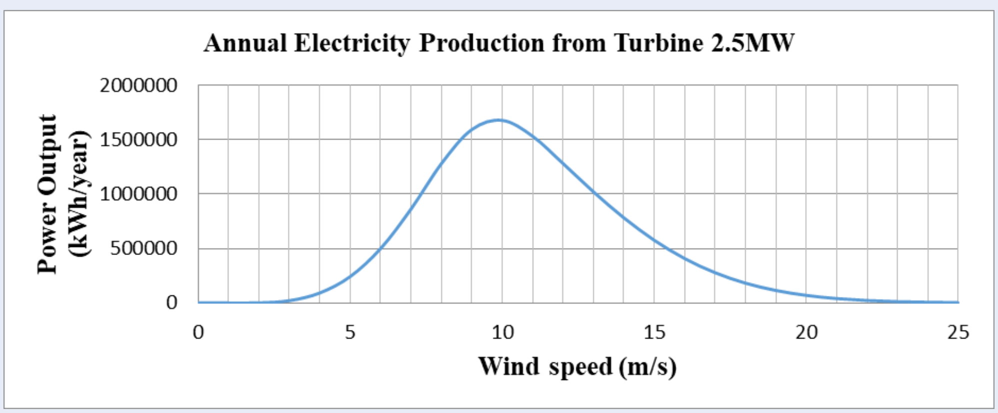

Figure 16: Annual electricity production chart of a 2.5MW Wind Turbine

Table 7: Wind speed frequency according to Weibull distribution

Wind Speed Frequency According to Weibull Distribution			
v = 0	m/s	0.00	h/year
v = 1	m/s	126.64	h/year
v = 2	m/s	289.98	h/year
v = 3	m/s	456.48	h/year
v = 4	m/s	607.53	h/year
v = 5	m/s	728.70	h/year
v = 6	m/s	809.99	h/year
v = 7	m/s	846.50	h/year
v = 8	m/s	838.70	h/year
v = 9	m/s	791.84	h/year
v = 10	m/s	714.73	h/year
v = 11	m/s	618.14	h/year
v = 12	m/s	512.99	h/year
v = 13	m/s	408.92	h/year
v = 14	m/s	313.31	h/year
v = 15	m/s	230.85	h/year
v = 16	m/s	163.61	h/year
v = 17	m/s	111.55	h/year
v = 18	m/s	73.18	h/year
v = 19	m/s	46.19	h/year
v = 20	m/s	28.05	h/year
v = 21	m/s	16.39	h/year
v = 22	m/s	9.21	h/year
v = 23	m/s	4.98	h/year
v = 24	m/s	2.59	h/year
v = 25	m/s	1.29	h/year

of wind speed must be considered carefully (see Figure 17). It reflects the level of random fluctuation in wind speed. It depends on the terrain surface and obstacles encountered by the wind on its flow path.

The basic formula for determining turbulence intensity[7] :

$$I = \frac{\sigma_v}{\bar{v}} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(v_i - \bar{v}\right)^2}}{\bar{v}} \qquad (4\text{-}2)$$

Where:

I : Turbulence intensity, (%)

σ_v*: Standard deviation of wind speed (m/s)*

v_i *: the individual wind speed measurement, (m/s)*

$\bar{v}$ *: average wind speed (m/s)*

This turbulence directly affects to lifespan of the turbine. Therefore, the IEC 61400-1 standard defines wind turbine classification as Table 10 .

Where, $V_{ref} = V_{tb}/0.2$ and I_{ref} is calculated at referred wind speed of 15m/s as indicated in Figure 18 according to the installation height.

From standard deviation channel of wind speed, the apparent turbulence intensity (ATI) is calculated by using formula 4-2:

Where:

Table 8: The power curve and operating data of the wind turbine 2.5 MW catalogue

The Characteristic Curve of Wind Turbine 2.5 MW			
v = 0	m/s	0.0	kW
v = 1	m/s	0.0	kW
v = 2	m/s	3.0	kW
v = 3	m/s	48.0	kW
v = 4	m/s	153.0	kW
v = 5	m/s	335.0	kW
v = 6	m/s	620.0	kW
v = 7	m/s	1023.0	kW
v = 8	m/s	1530.0	kW
v = 9	m/s	2015.0	kW
v = 10	m/s	2350.0	kW
v = 11	m/s	2480.0	kW
v = 12	m/s	2500.0	kW
v = 13	m/s	2500.0	kW
v = 14	m/s	2500.0	kW
v = 15	m/s	2500.0	kW
v = 16	m/s	2500.0	kW
v = 17	m/s	2500.0	kW
v = 18	m/s	2500.0	kW
v = 19	m/s	2500.0	kW
v = 20	m/s	2500.0	kW
v = 21	m/s	2500.0	kW
v = 22	m/s	2500.0	kW
v = 23	m/s	2500.0	kW
v = 24	m/s	2500.0	kW
v = 25	m/s	2500.0	kW

Column TI_{ave} is the value of average turbulence intensity according to wind speed v.

Column ST is a standard deviation of TI and to be calculated as the following formula[6] :

$$ST = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \qquad (4\text{-}3)$$

Where: n is the number of measurements

$\bar{x}$ is an average of the individual measurement and the formula can also be expressed as[6] :

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (4\text{-}4)$$

Column ATI is the apparent turbulence intensity. According to the Table 10[8] , value of ATI is calculated as follows:

$$ATI = TI + 1.28 \times ST \qquad (4\text{-}5)$$

Based on the calculated results in Table 11 and can be seen in the Figure 19 , the ATI wind speed of 15m/s is 17.48%. According to the IEC standard, the reference turbulence intensity I_{ref} is defined as:

$$I_{ref} = \frac{ATI}{\left(0.75 + \frac{5.6}{v_{15}}\right)} \qquad (4\text{-}6)$$

Table 9: Annual electricity production from wind turbine 2.5 MW

v = 0	m/s	-	kWh/year
v = 1	m/s	-	kWh/year
v = 2	m/s	869.95	kWh/year
v = 3	m/s	21,911.16	kWh/year
v = 4	m/s	92,951.72	kWh/year
v = 5	m/s	244,115.47	kWh/year
v = 6	m/s	502,194.42	kWh/year
v = 7	m/s	865,974.01	kWh/year
v = 8	m/s	1,283,211.33	kWh/year
v = 9	m/s	1,595,547.53	kWh/year
v = 10	m/s	1,679,626.08	kWh/year
v = 11	m/s	1,532,990.03	kWh/year
v = 12	m/s	1,282,466.94	kWh/year
v = 13	m/s	1,022,298.84	kWh/year
v = 14	m/s	783,283.68	kWh/year
v = 15	m/s	577,120.43	kWh/year
v = 16	m/s	409,020.14	kWh/year
v = 17	m/s	278,885.35	kWh/year
v = 18	m/s	182,954.05	kWh/year
v = 19	m/s	115,477.28	kWh/year
v = 20	m/s	70,124.48	kWh/year
v = 21	m/s	40,966.07	kWh/year
v = 22	m/s	23,020.26	kWh/year
v = 23	m/s	12,441.33	kWh/year
v = 24	m/s	6,465.85	kWh/year
v = 25	m/s	3,230.81	kWh/year

Table 10: Wind Turbine Classification following IEC standard

Basic parameters for the standard WTG classes I-IV							
	WTG Class		I	II	III	IV	
Parameters	Vref	(m/s)	50	42.5	37.5	30	Values specified by Designer
	Vave	(m/s)	10	8.5	7.5	6	
	A	Iref	0.16				
	B	Iref	0.14				
	C	Iref	0.12				

Source: IEC 61400-1 3rd Edition To classify these, it is based on V_{ref} and I_{ref} .

Table 11: Result of the Apparent Turbulence Intensity

Wind speed (m/s)	Ave. Turbulence Intensity, (TI ave)	Standard Deviation (ST)	Apparent Turbulence Intensity, (ATI)
v = 1	0.7555	1.3320	2.4604
v = 2	0.7296	0.4342	1.2854
v = 3	0.5010	0.2497	0.8206
v = 4	0.3652	0.1681	0.5803
v = 5	**0.2893**	**0.1264**	**0.4511**
v = 6	0.2374	0.1020	0.3680
v = 7	0.2023	0.0819	0.3072
v = 8	0.1817	0.0687	0.2696
v = 9	0.1613	0.0574	0.2348
v = 10	0.1474	0.0504	0.2120
v = 11	0.1474	0.0504	0.2120
v = 12	0.1357	0.0412	0.1883
v = 13	0.1321	0.0391	0.1822
v = 14	0.1288	0.0377	0.1770
v = 15	0.1269	0.0375	0.1748
v = 16	0.1206	0.0371	0.1682
v = 17	0.1133	0.0380	0.1619
v = 18	0.1098	0.0376	0.1579
v = 19	0.1015	0.0389	0.1514
v = 20	0.0942	0.0356	0.1397
v = 21	0.0883	0.0412	0.1411
v = 22	0.0922	0.0395	0.1428
v = 23	0.0859	0.0318	0.1266
v = 24	0.0839	0.0318	0.1246
v = 25	0.0594	0.0251	0.0915
v = 26	0.0607	0.0110	0.0749

Applying above formula 4-6, the I_{ref} is calculated approximately 15.56%.

The average wind speed at a height of 80m is 8.46m/s.

According to the IEC, the reference wind speed is calculated as:

$V_{ref} = V_{tb}/0.2 = 42.3$m/s.

By comparing V_{ref} and I_{ref} with Table 10 , the selected turbine class for installation is Class II-A.

Observation:

The right selection of turbine class is crucial, if choosing a lower class could affect turbine's performace due to unexpected wind gusts. Conversely, selecting a higher class turbine would increase the initial investment costs.

In order to validate the calculated both k and A value from section **Statistical characteristics of the data series for energy calculation**, the results in Figure 20 were cross-checked by using the WindPro software (see Figure 21) for comparision and verification with the same input data.

Conclusion

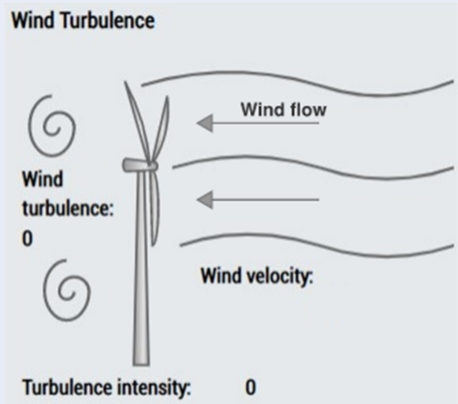

Figure 17: Model of wind flow and wind turbine

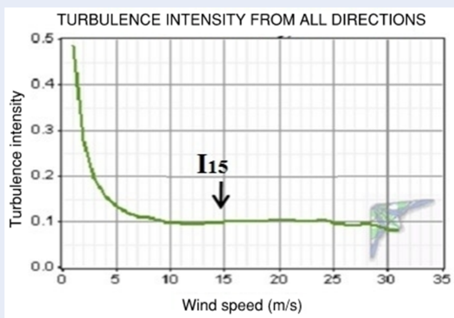

Figure 18: *Illustration of determining turbulence intensity at referred wind speed.*

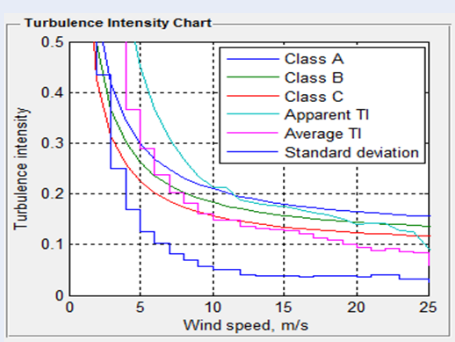

Figure 19: Calculated result of apparent turbulence intensity and 03 curves according to IEC.

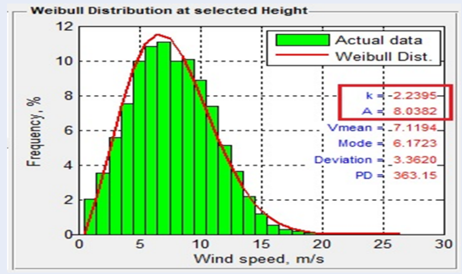

Figure 20: *Calculated results of characteristic parameters from simulation software*

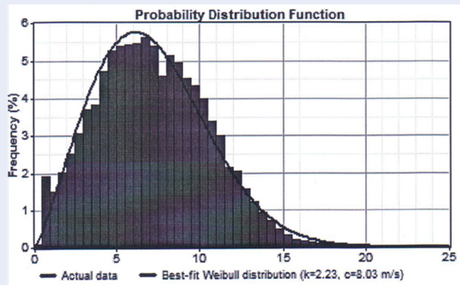

Figure 21: Calculated results of characteristic parameters from WindPro 2.5

In terms of methodology, it can be observed that the results of the characteristic parameters are the same, affirming the reliability of the simulation software programmed. This is considered a critical step in assessment the feasibility of an entire wind power project.

CONCLUSION AND DISCUSSION

To avoid inaccurate forecasts and increased experimental costs that waste resources, each wind farm project, both existing and planned for the future, must be performed in detailed analysis. By creating computational models as illustrated in Figure 22 , we establish a basis for assessing the wind energy potential of a given area and data, estimating the maximum annual electricity production a turbine can generate with highly reliable and accurate analysis results, and ultimately evaluating turbulence intensity conditions to select the appropriate turbine type for the intended installation site.

Furthermore, to optimize the design and operation of the system in the future, the research proposes the development of digital twin (see Figure 23) and machine learning applications for wind farms [14] . This involves establishing Physics-based models to simulate operating conditions under various scenarios (what-if sim-

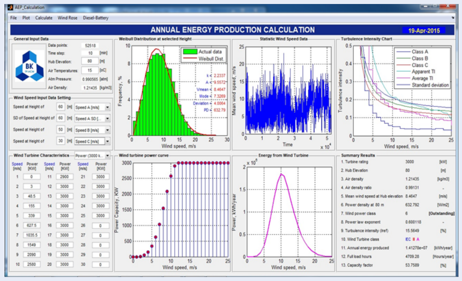

Figure 22: The Analytical Modelof Annual Energy Potential Calculation.

ulations) due to the continuous changes in input variables. Such analyses will enable appropriate adjustments to enhance the overall system efficiency. The benefits of digital twin somution include:

- Optimizing the placement of wind turbines to maximize wind energy capture.
- Increasing the electricity output of the wind farm.
- Reducing operational and maintenance costs.
- Extending the lifespan of the equipment.

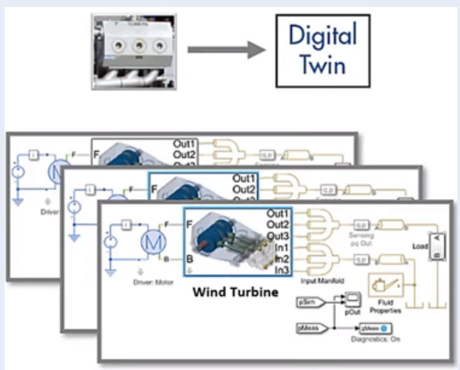

Figure 23: Digital twin modelcan predict failures and optimal design adjustment

Finally, the development of a hybrid model that combines Physics-based modeling and machine learning is proposed. This model will learn from actual operational data, improving and enabling an evaluation of the performance of system components and providing more accurate and optimal adjustment signals[11], [12].

COMPETING INTERESTS

We hereby confirm that there are no conflicts of interest regarding the entire content of this paper.

AUTHORS' CONTRIBUTIONS

Truong Trong Hieu: Collected input data, processed and performed data analysis, developed algorithms, and built analytical software with graphical visualization, wrote and revised the manuscript.

Nguyen The Bao: Advise mathematical formulas and contributed to manuscript revision.

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Open Access Full Text Article

Bài nghiên cứu

Xây dựng mô hình phân tích đánh giá tiềm năng gió để chọn cấu hình turbine phù hợp và đề xuất nghiên cứu tối ưu thiết kế trang trại điện gió

Trương Trọng Hiếu[1], Nguyễn Thế Bảo[1,2,*]

TÓM TẮT

Trước khi một trang trại gió được xây dựng, việc đánh giá tiềm năng gió tại khu vực dự kiến lắp đặt tuabin cần phải được thực hiện như một điều kiện tiên quyết. Để đạt được hiệu suất cao nhất, các kỹ sư thiết kế cần nắm vững các khái niệm chính và có hiểu biết sâu sắc về đánh giá năng lượng gió. Bài báo này áp dụng lý thuyết phân bố Weibull và các nguyên lý khí động học để xây dựng mô hình phân tích, đánh giá các tiêu chuẩn và ước tính sản lượng điện hằng năm dựa trên dữ liệu đầu vào thô được thu thập trong một năm. Kết quả tính toán các thông số đặc trưng của gió, bao gồm hệ số hình dạng, tỷ lệ và mật độ công suất tại khu vực khảo sát tương ứng với độ cao 80m, được xác định chi tiết thông qua phần mềm mô phỏng. Kết quả phân tích cũng cho thấy tiềm năng gió tại đây được xếp vào loại rất cao (cấp 6), và cần lựa chọn cấu hình tuabin tối thiểu loại II-A để có thể chịu được điều kiện gió này. Vì chi phí đầu tư ban đầu của một trang trại gió sẽ được xác định dựa trên kết quả mô phỏng, nghiên cứu này hướng tới việc kết hợp phương pháp tính toán sử dụng trong nghiên cứu với việc ứng dụng giải pháp song sinh kỹ thuật số (digital twin) và học máy (machine learning) cho các trang trại gió, nhằm tạo ra một bản sao kỹ thuật số chính xác của hệ thống thực tế. Bằng cách này, hoạt động của hệ thống trong thời gian thực sẽ được giám sát và liên tục cập nhật vào mô hình mô phỏng để hiểu và dự đoán hành vi của nó. Từ đó, các điều chỉnh tối ưu trong thiết kế và vận hành sẽ được thực hiện để nâng cao hiệu quả tổng thể của hệ thống và giảm thiểu sai sót cũng như rủi ro cho nhà đầu tư.

Từ khoá: Phân tích đánh giá tiềm năng gió, ứng dụng song sinh kỹ thuật số, công nghệ học máy trong điện gió tại Việt Nam.

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