



Implementation Assessment of the Offshore Wind Turbine (OWT) for Remote Regions' Electrification in Indonesia Based on Geographical Potential and Economic Attractiveness

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Abstract

Indonesia's energy supply predominantly relies on fossil fuels, contributing significantly to CO₂ emissions and environmental pollution. This study investigates the potential of offshore wind turbines for electrification in Indonesia's remote regions: Papua, Maluku, and Ujung Kulon, focusing on optimization and economic feasibility. The methodology involves utilizing MERRA-2 reanalysis data from the National Aeronautics and Space Administration (NASA) to calculate various wind turbines' annual energy production (AEP) and capacity factors. Sensitivity analysis was performed on crucial turbine parameters such as cut-in speed, cut-off speed, and rated speed to optimize turbine selection. The findings indicate that the suitable turbines for the three locations are turbines with a rated speed of 10-12 m/s with a rated power of 3-5 MW. With the highest average wind speed of 6.94 m/s at 100 m, Papua has the best prospect of producing AEP of 15268.14 MWh for a single turbine with a capacity factor of 39.11%. The calculation of economic potential is also explained in the form of a levelized cost of energy (LCOE) using a scaling model. This research supports Indonesia's commitment to achieving net-zero emissions by 2060 and highlights the potential of offshore wind energy as a sustainable solution for remote region electrification.

Keywords: Renewable energy; Wind resource assessment; Horizontal-Axis Wind Turbine (HAWT); Turbine optimization; Weibull distribution; Economic assessment.

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1. Introduction

Energy is a critical issue for economic and industrial development in a country, and it is also deployed in the Sustainable Development Goals (SDGs) declared by the United Nations. Indonesia's primary energy mix (see Fig. 1^[1]) in Q3 2021 is still dominated by fossil fuels: coal, gas, and oil. Renewable energy only contributed 11.2%, with biofuels at 4.2%, hydro at 2.7%, geothermal at 2.0%, and others (excluding biomass) at 2.2%. Coal contributed the most CO₂ emissions in 2021, amounting to 303.15 million tons or around

48.95% of total CO₂ emissions in Indonesia.^[2] With the dominance of fossil fuels in the energy supply, the most significant problems are environmental pollution and climate change due to greenhouse gas emissions.^[3] Throughout 2021, primary energy supplies in Indonesia reached 1,545,557,232 Barrels of Oil Equivalent (BOE) with a final energy consumption of 909,244,973 BOE.^[4] Energy demand will continue to increase from year to year. The final energy demand in 2050 is projected to reach 548.8 Mega Tons of Oil Equivalent (MTOE), with dominance in the industrial and transport sectors.^[5]

As an archipelagic country, Indonesia's geographical condition results in energy distribution that still needs to be improved. Indonesia's disconnected land and vast stretches of sea cause difficulties and limited control over remote regions in Indonesia. Until Q1 in 2021, the electrification ratio in Indonesia reached 99.28%, indicating that there are still around 5 million people who do not enjoy electricity.^[6] Data

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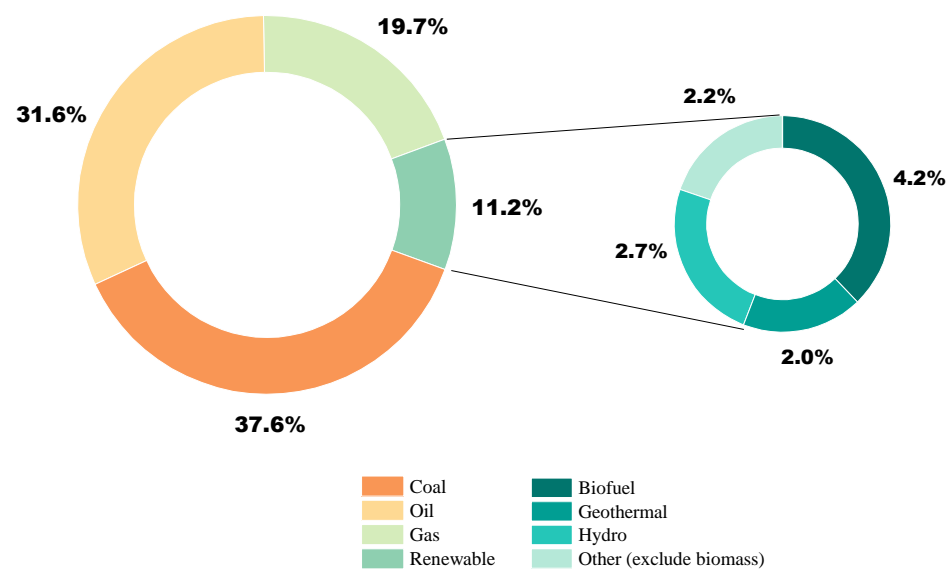


Fig. 1 Indonesia's primary energy mix in Q3 2021, redrawn from [1].

from the Central Statistics Agency (*Badan Pusat Statistika - BPS*) shows 62 lagging regions in Indonesia, with the percentage of poor people reaching 26.43% in 2020.^[7] Data from the State Electricity Company (*Perusahaan Listrik Negara-PLN*) in 2021 shows that electricity prices outside Java can reach IDR 1,438.59/kWh for household electricity costs.^[8]

Based on these backgrounds, ocean energy can be a solution, especially offshore wind energy. Offshore wind plays a crucial role in net zero emissions (NZE), and offshore wind energy is significantly higher than in onshore areas.^[9] This higher amount of offshore wind energy is due to several factors: a) offshore wind has better wind quality where wind speeds are more remarkable, even increasing with distance to shore, tends to be laminar, and has low turbulence effects,^[10] b) the large space in the sea area can be used for the installation of more offshore wind power plants,^[11] c) a much higher capacity factor compared to onshore.^[12]

Several researchers studied the potential of renewable wind energy both onshore and offshore. Langer *et al.*^[13] researched the potential for offshore wind energy in countries with low wind speeds, explicitly focusing on Indonesia. The methodology of this study involved utilizing 20 years of hourly wind speed data from the European Centre for

Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) dataset. This data was then bias-corrected using information from the Global Wind Atlas to map potential sites for offshore wind farms across Indonesia accurately. Additionally, the study evaluated turbines designed for low wind speed conditions, analyzing their technical feasibility and economic viability separately. This comprehensive approach ensured a detailed assessment of suitable locations and the potential for developing offshore wind energy in the region. The result stated that low-wind-speed turbines have the potential to generate up to 6,816 TWh/year, which is 25 times Indonesia's 2018 electricity production and three times the country's projected generation for 2050. Globally, these turbines could produce up to 166 PWh/year.

Fauzy *et al.*^[14] investigated the potential of wind energy in Indonesia, focusing on offshore wind farms. The study delves into Indonesia's wind energy resources, wind farm layout optimization, and cost components. The specific location investigated was Water Island, where wind speeds were measured at a height of 100 meters. Wind data was obtained from the Weather Research and Forecasting (WRF) model. The WRF dataset, with a resolution of approximately 0.029° (around 3 km), is driven by ECMWF Reanalysis (ERA)-Interim global data covering 2004 to 2015. Three turbines were used, with rated powers of 1800 kW, 2300 kW, and 2000 kW, respectively. After preparing all necessary data, simulations were run using WindSim software. The findings indicate the highest time-based availability and a capacity factor of 46%. The levelized cost of electricity, at 0.082 USD/kWh, is competitive with the cost of electricity generated from fossil fuels in Indonesia, which ranges between 0.07 and 0.15 USD/kWh.

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Study form Nurlatifah *et al.*^[15] assessed Indonesia's offshore wind energy potential by analyzing a 30-year NCEP-NCAR reanalysis dataset. Despite Indonesia's equatorial location, typically characterized by marginal wind speeds, the research identified three promising regions: Aceh, Southern Java, and Southern Papua. The findings revealed that 86% of wind speeds in Aceh, 80% in Southern Java, and 81% in Southern Papua exceed the cut-in speed for the NREL 5 MW turbine, with higher wind speeds during the dry season and no extreme wind speeds above 25 m/s, indicating stable conditions suitable for offshore wind farms.

Hesty *et al.*^[16] investigated potential assessment and investment for wind energy in Indonesia using the Weather Research and Forecasting (WRF) model with data from a Cross-Calibrated Multi-Platform (CCMP) Reanalysis satellite. The Geographic Information System (GIS) is utilized to visualize wind speeds by province using wind maps for the entire region of Indonesia. The modeled data is validated using empirical measurements from three meteorological masts in Jayapura, Bantaeng, and Sukabumi. The results demonstrate that the WRF model reliably estimates mean wind speeds across all provinces in Indonesia. The wind speed data, displayed on a GIS map, provides valuable information for wind energy planning at both national and regional levels.

Based on Wijanarko *et al.*^[17] meteorological data from 2015 to 2019 was used to estimate the Weibull distribution function, wind power, and energy density for ten meteorological stations across three provinces. Monthly and yearly variations in wind speed were analyzed, revealing that the shape and scale parameters varied significantly at each location. The highest wind power potential was found in Jayawijaya City, with 36.23 W/m². Monthly wind speeds varied considerably at each site, ranging from 2.27 to 2.9 m/s in Jayawijaya and 0.25 to 0.58 m/s in the Bogor Regency.

Ranthodsang *et al.*^[18] conducted a study on offshore wind power in Thailand, a Southeast Asian country with a similar climate to Indonesia. This paper presents an assessment of offshore wind resources and a feasibility analysis for offshore wind power on Thailand's western coast. The study uses coupled mesoscale atmospheric modeling, microscale Computational Fluid Dynamics (CFD) wind flow modeling, and a climatic database. Wind maps at elevations of 80 m, 90 m, and 120 m above mean sea level are created and validated using wind data collected from nine meteorological masts along the Andaman Sea and the Strait of Malacca. The result stated that the wind resource map at 120 is the best area for wind power development, where the mean annual wind speeds are 5.5-6.0 m/s. Offshore wind power plants using a 3.3 MW

turbine can produce annual energy of over 13 GWh/year with the lowest leveled cost of energy at 0.188 USD/kWh.

Maandal *et al.*^[19] studied offshore wind energy in the Philippines. The analysis is divided into four phases: applying exclusion criteria, conducting a technical analysis, performing an economic assessment, and conducting a sensitivity analysis. The results are spatially visualized using the ArcGIS 10.5. The turbines SWT-3.6-120 and 6.2 M126 Senvion were evaluated in the technical analysis. Offshore wind speed data were extrapolated from 80 m to 90 m and 95 m using the power law. Wind power density, wind power, and annual energy production were calculated based on the extrapolated wind speeds. The results stated that capacity factor ranges from ~42% to ~50% for SWT-3.6-120 and ~38.56% to ~48% for 6.2M126 turbines

In the existing literature, no specific rationale is provided for turbine selection to maximize the potential of the studied areas. Therefore, this paper aims to investigate the potential of offshore wind turbines in Indonesia's remote regions and optimize turbine selection using sensitivity analysis by deploying regression methods. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) reanalysis data from NASA calculates annual energy production and capacity factor. The cost of energy (COE) will be presented as part of a feasibility study. This paper also supports the Indonesian government's commitment to achieving net zero emissions (NZE) by 2060.

2. Methodology

2.1 Weibull distribution function

A statistical approach, namely Weibull distribution, was used for wind data analysis.^[20] Based on the selected wind speed data, the Weibull distribution can be described as a probability density function (PDF) given as equation (1), respectively.^[21]

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right], (k > 0, v > 0, c > 1) \quad (1)$$

where $f(v)$ is the wind speed probability for speed v , c is the Weibull scale parameter, and k is the shape parameter. The c and k values are determined by the relationship.^[22]

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad (2)$$

$$c = \frac{\bar{v}}{\Gamma(1+1/k)} \quad (3)$$

where \bar{v} is the mean wind speed in m/s, σ is the standard deviation, Γ is the gamma function. For calculating \bar{v} , σ , and $\Gamma(x)$ can be defined by the following equations: (4), (5), and (6).^[23]

$$\bar{v} = \frac{1}{n} \sum_{i=1}^n v_i \quad (4)$$

where v_i is measured wind speed in m/s and n is the total measurement period.

$$\sigma = \left[\left(\frac{1}{n-1} \sum_{i=1}^n (v_i - \bar{v})^2 \right) \right]^{0.5} \quad (5)$$

$$\Gamma(x) = \int_0^\infty \exp(-u) u^{x-1} dx \quad (6)$$

2.2 Wind energy resources

2.2.1 Wind data measurement

This study obtained wind speed data from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resource (POWER) data access viewer. Meteorological parameters are derived from NASA's Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective Analysis for Research and Application Version 2 (MERRA-2).^[24] NASA provides MERRA-2 reanalysis data via the Goddard Earth Sciences Data and Information Services Center and supersedes the earlier version of MERRA.^[25] Data retrieval based on longitude and latitude coordinates inputted in NASA POWER. Data obtained is hourly data for 12 months (01/10/21 - 01/10/22). The measurement height at each location is 10 and 50 meters. Wind direction was also obtained during data collection.

Table 1. Typical shear exponents for different site conditions.^[27]

Terrain type	Land Cover	Approximate range of annual mean wind shear exponent
Flat or rolling	Low to moderate vegetation	0.12-0.25
Flat or rolling	Patchy woods or forest	0.25-0.40
Complex, valley (sheltered)	Varied	0.25-0.60
Complex, valley (gap or thermal flow)	Varied	0.10-0.20
Complex, ridgeline	Low to moderate vegetation	0.15-0.25
Complex, ridgeline	Forest	0.20-0.35
Offshore, temperate	Water	0.10-0.15
Offshore, tropical	Water	0.07-0.10

2.2.2 Wind speed variation with height

Wind data for this study were given at 10 m and 50 m above ground level. Determining the wind speed at a certain hub height is very important because it can help estimate the energy generated by the turbine. In general, wind speed will increase with height. The wind power law equation relates the

wind speeds at two different heights in the following manner.^[26]

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1} \right)^\alpha \quad (7)$$

where v_1 (m/s) is the wind speed at height h_1 (m), v_2 (m/s) is the wind speed at height h_2 (m), and α is wind shear exponent. The typical shear exponents for different conditions are shown in Table 1.^[27]

2.3 Power curve model and Betz limit

A wind turbine power curve consists of 3 main points: A, B, and C (see Fig. 2). Point A represents the cut-in wind speed, point B signifies the rated wind speed, and point C reflects the cut-off wind speed.^[28]

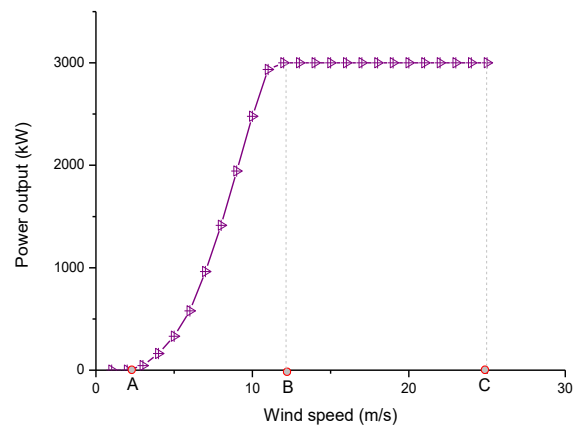


Fig. 2 An abstract power curve.

The power curve is usually specified for a commercial wind turbine. Wind turbine manufacturers release power curves assuming ideal conditions. Theoretical wind power is obtained using the following equation:^[29]

$$P = \frac{1}{2} C_p \rho \pi R^2 v^3 \quad (8)$$

where C_p is the wind turbine power coefficient, ρ is the air density in kg/m^3 , R is the radius of the wind rotor in m^2 , and v is the wind speed in m/s . The power coefficient is obtained using equation (9).

$$C_p = \frac{1}{2} \left(1 + \frac{v_3}{v_1} \right) \left(1 - \left(\frac{v_3}{v_1} \right)^2 \right) \quad (9)$$

where v_1 is the wind speed before passing the turbine in m/s and v_3 is the wind speed before passing the turbine in m/s . By setting the first derivation of equation (9) to zero, the maximum power coefficient is equal to:

$$C_{p, \text{Betz}} = \frac{16}{27} = 0.593 \quad (10)$$

Naturally, only a part of the total wind power can be extracted by a wind turbine. The maximum wind power extracted is limited by the Betz limit of $C_{p, \text{Betz}} = 0.593$.^[30] Illustration for Betz limit can be seen in Fig. 3.

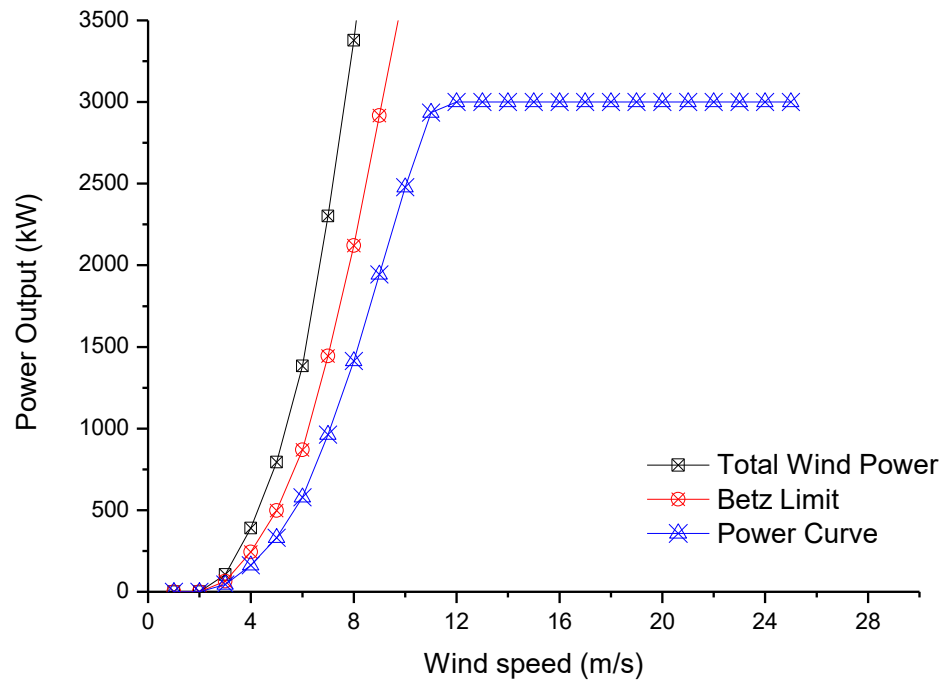


Fig. 3 Illustration for Betz limit.

2.4 Energy produces by wind turbine

Annual energy production is the energy produced by a wind turbine for one year. Annual energy production can be calculated with the equation (11);

$$AEP = \sum_{k=1}^m [p(V_k) \times f(V_k) \times n] \quad (11)$$

where AEP is annual energy production in MWh, $p(V_k)$ is the power curve in MW, $f(V_k)$ is the relative frequency of wind, n is the number of hours in a year, and m is the number of bins (usually 1 m/s as the bin width).

Due to the fluctuating wind distribution, the turbine cannot produce the maximum energy capacity. Therefore, the capacity factor (CF) is the energy that can be generated compared to its maximum capacity. CF for a wind turbine can be found by the following equation (12).^[31]

$$CF\% = \frac{AEP}{Power\ Rated \times n} \times 100\% \quad (12)$$

2.5 Economic analysis

This paper calculates the economic potential based on the scaling model by Fingers *et al.*^[32] in the National Renewable Energy Laboratory (NREL). Cost estimates were projected based on the power rate, rotor diameter, hub height, and other primary turbine devices. For this purpose, the following equation was employed.^[32]

$$CEO = \frac{(FCR \times ICC)}{AEP_{net}} + AOE \quad (13)$$

where CEO is the cost of energy in \$/kWh, FCR is fixed charge rate in 1/y (constant \$), ICC is initial capital cost in \$, AEP_{net} net annual energy production in kWh/y and AOE is

annual operating expenses in \$. AOE is calculated using the following equation (14).

$$AOE = LCC + \frac{(O\&M + LRC)}{AEP_{net}} \quad (14)$$

where LCC is land lease cost in \$, $O\&M$ is levelized operating & maintenance cost in \$, LRC and levelized replacement/overhaul cost in \$.

FCR means a percentage factor, which can change over time and is set to 11.58%. FCR includes component costs, administration, operation and maintenance, taxes, and capital costs associated with ownership. For offshore wind turbines, LCC can be replaced with bottom lease cost, where the lease cost is similar to offshore drilling cost.

2.6 Regression method

2.6.1 Linear regression

Generally, a linearized model can be obtained by a piecewise approximation to the equation of a straight line.^[28] The linear regression has an equation of the form:^[33]

$$Y = \beta_0 + \beta_1 X + e \quad (15)$$

where Y is the dependent variable, X is the independent variable, β_0 and β_1 are the regression coefficients, and e is an error.

2.6.2 Polynomial regression

Polynomial regression is an evaluable method. The general form of the polynomial regression is as follows.^[34]

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \dots + \beta_m X^m e \quad (16)$$

where Y is the dependent variable, X is the independent variable, $\beta_0, \beta_1, \beta_2, \dots, \beta_m$ is regression coefficients, m is the polynomial degree, and e is the error between the model and the observation.

2.6.3 Quality of the model

The quality of fit of the linear and polynomial model to a given set of observed data can be judged using the coefficient of determination (R^2). The coefficient of determination can be calculated with the equation (17).^[35]

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum(\hat{Y}_i - Y_i)^2}{\sum(\bar{Y} - Y_i)^2} \quad (17)$$

where SSE is the sum square of errors, SST is the sum square of the total, and \bar{Y} is the mean prediction value. The value of R^2 varies between 0 and 1. The approach of R^2 to 1 indicates good agreement between the values.

3. Site selection

Site selection is the key to a successful offshore wind turbine project from a technical and economic aspect. Based on the data in Table 2, it can be concluded that the main criterion for offshore wind projects for site selection is wind resources (wind speed and wind directions). An offshore wind turbine project must have constant and intense wind speeds. Sea areas with an average speed of fewer than 6 m/s are unsuitable for offshore wind farms. The technology developed for offshore wind turbine foundations (due to water depth variations) consists of fixed and floating foundations such as monopile, jacket, tripod, flotation, and gravity base that can be applied to a maximum water depth of 60 m. Distance to shore affects wind speed and installation costs. Wind speed will be more incredible when the distance to shore is longer. Distance to shore also affects noise impact (construction and operation). Based on the literature review, offshore wind turbines' average distance to shore is < 20 km. In the economic aspect, installing offshore wind turbines considers commercial feasibility and local economic benefits. Site selection in this study considers the factors described above.

Indonesia is geographically located between the continents of Australia and Asia and between the Indian Ocean and the Pacific Ocean. Meanwhile, Indonesia is geographically located at 6° North Latitude (NL) - 11° South Latitude (SL) and 95° East Longitudinal (EL) - 141° East Longitudinal (EL). Indonesia's geographical position results in Indonesia having only 2 seasons, namely the dry season from April to October and the rainy season from October to April, which is influenced by the movement of the monsoon winds. Astronomically, Indonesia is located on the equator. As a result, the distribution and potential of wind-generated are not too high around the equator.

The potential of wind energy in Indonesia can be seen in Fig. 4. It is shown that areas with wind potential > 6 m/s are

Table 2. Literature review for offshore wind project criteria.

Reference	Year	Country	Criteria for offshore wind project
[36]	2012	Greece	Average wind speed, distance to protected areas, distance to ship route, distance from the shore, and connection to the electricity networks
[37]	2015	Iran	Resource technical, depth and height, environmental issues, proximity to facilities, economic aspects, and culture
[38]	2016	China	Wind resource, construction and maintenance condition, supporting conditions onshore, environmental impact, economic, and social benefit.
[39]	2017	Baltic States	Performance objective, cost objective, and reliability objective
[40]	2018	Greece	Wind velocity, water depth, distance from areas of environmental interest, distance from residential network
[41]	2019	Turkey	Wind resource, water depth, distance to the coast, underwater pipelines, coastal waters, military zones, shipping and navigation routes, and pipelines.
[42]	2019	Turkey	Wind potential, territorial water, military areas, civil aviation, shipping routes, pipelines and underground cables, social concern, environmental concern, and sea depth.
[43]	2020	China	Wind resource, construction, economics, environment, society, and risk.
[44]	2021	Egypt	Wind resource, conditional onshore, construction, environmental, economic, and societal return.
[45]	2022	Turkey	Average offshore wind speed at 100m height, offshore human activities, distance to existing large ports, social acceptance, water depth, environmental concerns, soil conditions and earthquake hazard, electricity grid connection, territorial water, military zones, shipwrecks, civil aviation, existing pipelines and cables in the seabed, and offshore natural gas.

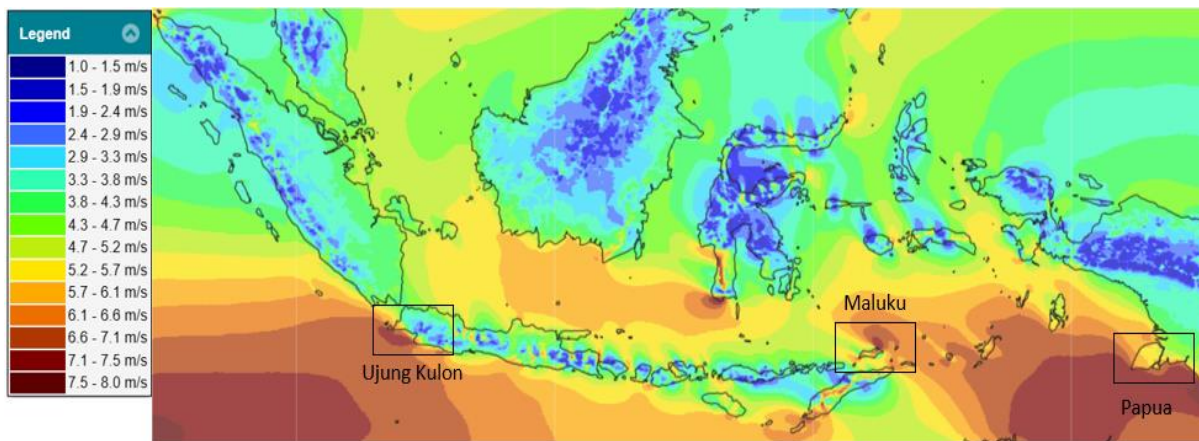


Fig. 4 Map of wind speed in Indonesia at 100 m.^[48]

located in Papua, Maluku, and Ujung Kulon. The three areas are remote regions in Indonesia that are a long distance from the central government in Java. The waters around the coast of the three locations are classified as shallow waters with water depth <5 m at a distance of 10 km from shore. Wind data measurements were carried out using the method described in section 2.2.1, obtained wind speed and wind direction data at the height of 10 and 50 meters. Using equation (7), the average wind speed at the height of 100 meters in Papua is 6.94 m/s, making it a location with tremendous offshore wind energy potential. Papua's electrification status in 2021, contained in Table 3, shows an electrification ratio of 95.43%. There are still 38,107 households that still need to be electrified.^[46] The installed power plant capacity in Papua is also far behind that of Java. The local electricity tariff in Papua is also relatively expensive, reaching 15.02 \$¢.^[47]

The second location is Maluku; the geographical condition

of Maluku consists of coastal areas and small islands with many straits and bays. Using the same method as data collection in Papua, the average wind speed at the height of 100 m is 6.05 m/s. In Table 3, the electrification ratio of Maluku is lower than that of Papua, which is only 92.44%, and there are still approximately 31,616 households that need to be electrified.^[46] The local electricity tariff in Maluku is higher than in Papua by 17.96 \$¢.^[47]

The last location that has offshore wind energy potential is Ujung Kulon. Ujung Kulon is located in western Indonesia and adjacent to Banten, where the wind speed at 100 m is 5.66 (the lowest among the three selected locations). The electrification ratio of this place has reached 99.99%, and the local electricity tariff is also the cheapest among the three locations. The wind speed sampling location for the three locations can be seen in Fig. 5. The electrification status and detailed site selection can be seen in Tables 3 and 4.

Table 3. Electrification status in 2021.^[46-47]

Variable	Papua	Maluku	Ujung Kulon
Power plant installed capacity (MW)	690	10090.08	356.12
Power capable of generating electricity (MW)	605.72	9522.85	242.7
Electric power production (GWh)	1547.96	297.59	71.27
Electrification ratio (%)	95.43	92.44	99.99
Local electricity tariff (\$¢)	15.02	17.96	5.81

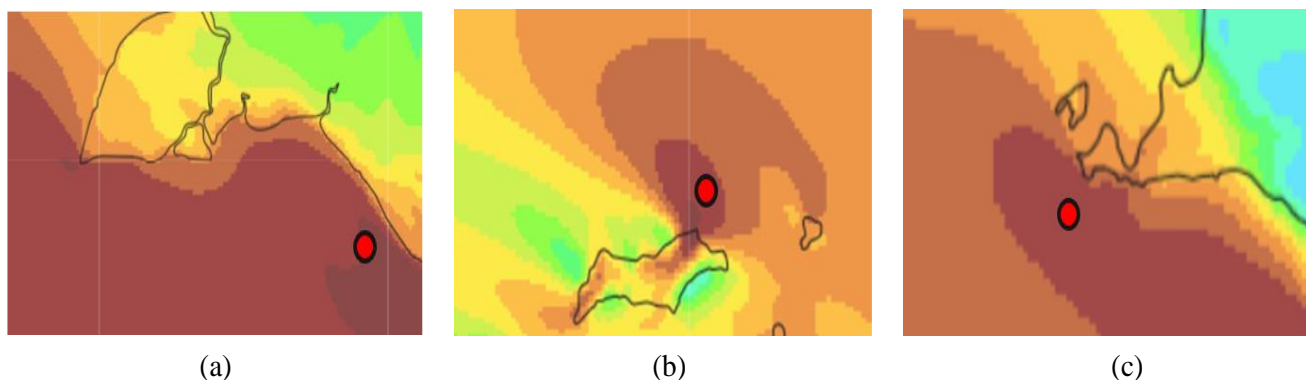


Fig. 5 Longitude and Latitude of (a) Papua, (b) Maluku, (c) Ujung Kulon.^[48]

Table 4. Detail site selection.

Variable	Papua	Maluku	Ujung Kulon
Longitude	8°54'24.8"S	7°28'49.1"S	6°52'35.2"S
Latitude	140°34'56.3"E	126°38'20.8"E	105°12'30.3"E
Height (m)	100	100	100
Distance to shore (km)	10	10	10
Water depth (m)	< 5	< 5	< 5
Annual average wind speed (m/s)	6.94	6.05	5.66
Standard deviation	2.69	2.94	2.56
Period	01/10/21 – 01/10/22	01/10/21 – 01/10/22	01/10/21 – 01/10/22
Weibull parameters	Scale (2.8197) Shape (7.1991)	Scale (2.1527) Shape (6.5862)	Scale (2.3477) Shape (6.1677)

The wind speed distribution of the three locations is shown in Fig. 6. Wind speed distribution from Papua has a scale and shape Weibull parameters values of 2.8197 and 7.1991. Wind

speed distribution from Maluku has a scale and shape Weibull parameters of 2.1527 and 6.5862. Wind speed distribution from Ujung Kulon has a scale and shape Weibull parameters of 2.3477 and 6.1677. From Fig. 7, for three locations, the wind speed with high values comes from the same direction, around 130° (southeast), with speeds between 12-14 m/s. In Fig. 8, the frequency of occurrence for wind direction in Indonesia for one year shows a tendency towards approximately 130° (southeast) and 300° (northwest). This is due to the effect of the seasons in Indonesia, namely the rainy and dry seasons. Both seasons are affected by the west monsoon and east monsoon. The west monsoon is a wind that blows from Asia. The wind then moves towards Australia through the Indian Ocean. The west monsoon occurs from December to February, with the first transition to the change of season in March to May.^[49] The west monsoon causes Indonesia to experience the rainy season. During the rainy season, the frequency of winds is relatively low (see Table 5 and Fig. 9). The direction of the west monsoon comes from the north-westerly direction (see Fig. 8). The east monsoon is the wind that blows from Australia to Asia through Indonesia. The east monsoon occurs from June to August, with a second transition to the change of season in September to

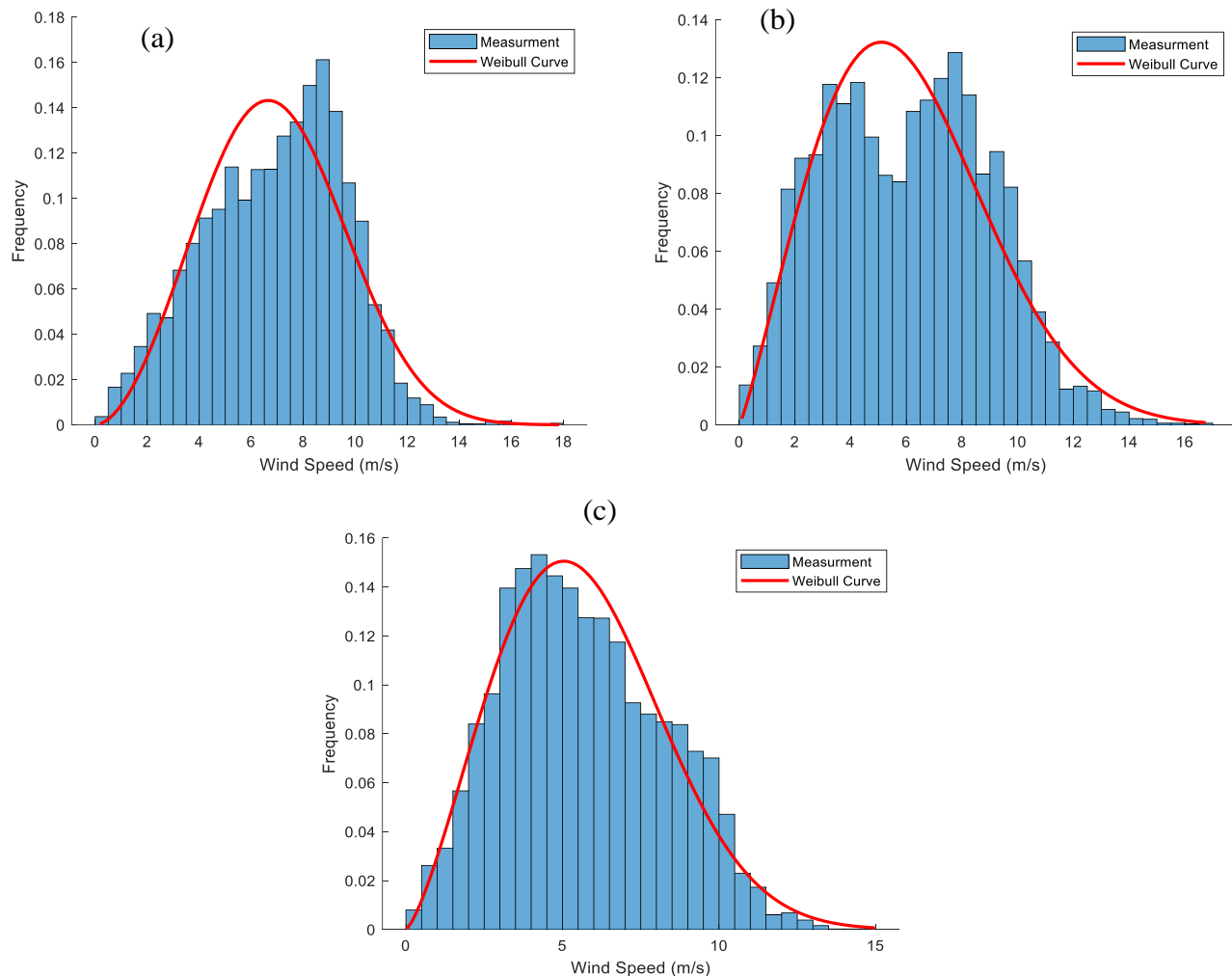


Fig. 6 (a) Wind speed distribution in Papua, (b) Wind speed distribution in Maluku, (c) Wind speed distribution in Ujung Kulon.

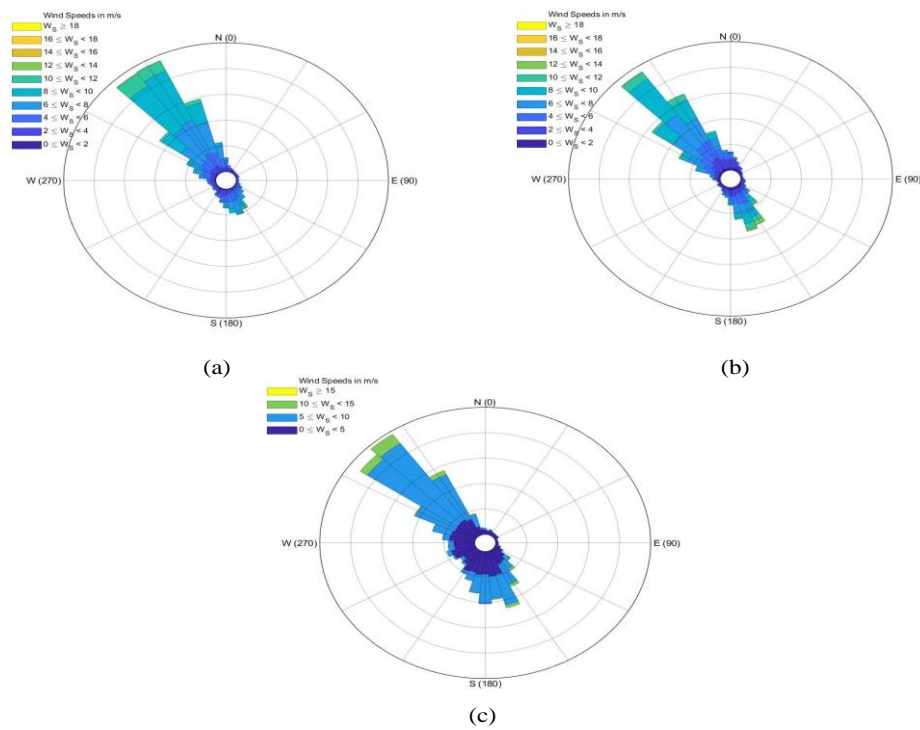


Fig. 7 (a) Wind rose in Papua, (b) Wind rose in Maluku, (c) Wind rose in Ujung Kulon.

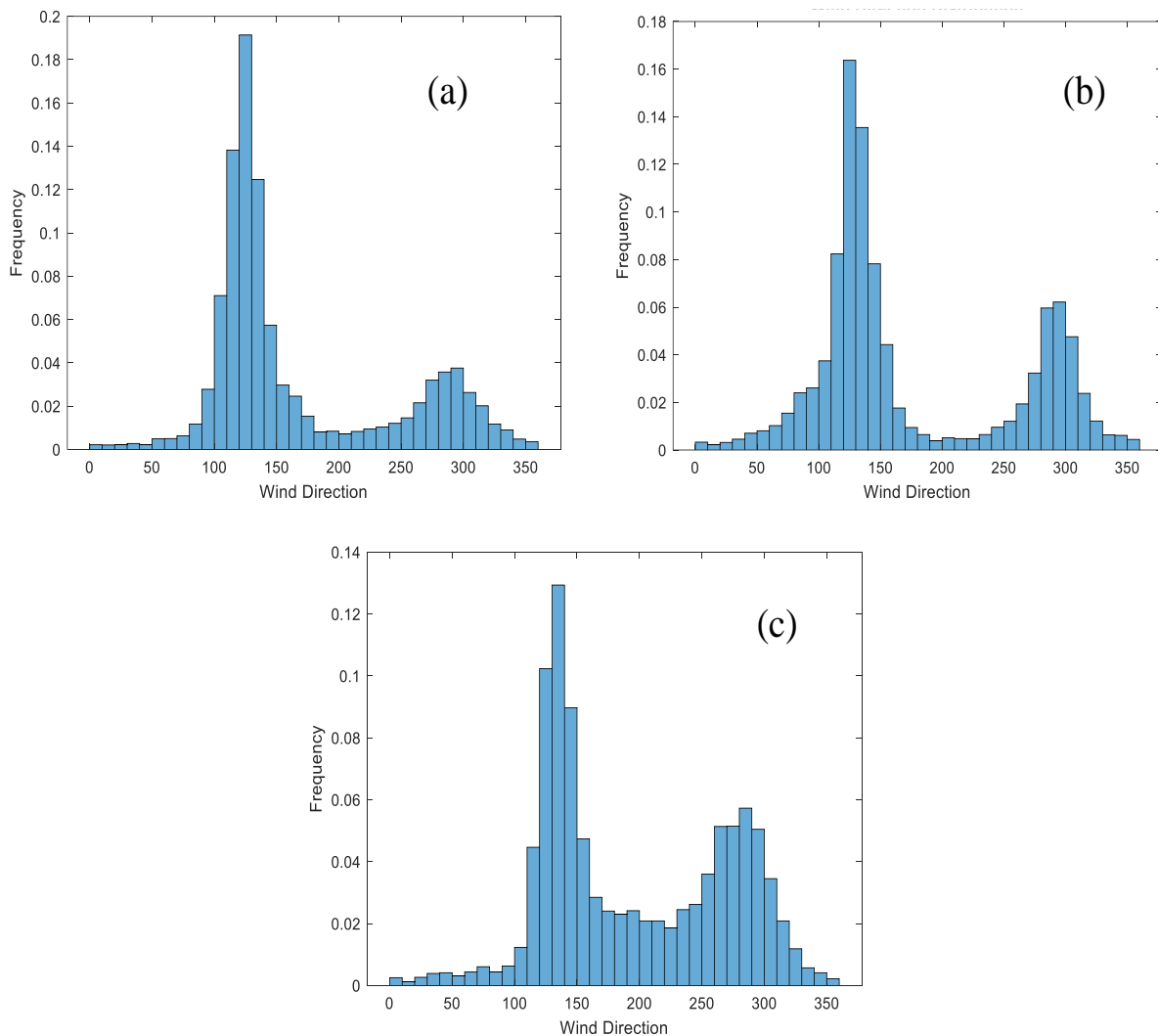


Fig. 8 (a) Wind direction in Papua, (b) Wind direction in Maluku, (c) Wind direction in Ujung Kulon.

Table 5. Monthly parameters.

Month	Papua			Maluku			Ujung Kulon		
	Avg. wind speed	Weibull parameters		Avg. wind speed	Weibull parameters		Avg. wind speed	Weibull parameters	
		<i>c</i>	<i>k</i>		<i>c</i>	<i>k</i>		<i>c</i>	<i>k</i>
January	6.14	3.404	6.837	7.59	4.096	8.361	4.06	4.566	2.738
February	6.06	2.137	6.837	6.84	1.703	7.662	6.41	7.224	2.541
March	4.50	2.263	5.084	3.56	2.230	4.024	4.93	5.512	2.838
April	5.00	2.414	5.631	4.12	2.219	4.636	4.17	4.690	2.646
May	7.00	3.878	7.728	6.97	3.664	7.747	4.66	5.265	2.217
June	8.99	5.327	9.732	8.00	3.927	8.851	4.89	5.518	1.929
July	9.27	7.050	9.880	8.63	6.805	9.195	6.77	7.556	3.161
August	9.58	8.755	10.095	8.27	6.636	8.847	8.28	9.092	4.459
September	8.40	6.331	9.019	6.09	4.018	6.730	7.17	8.009	3.074
October	6.98	4.361	7.652	4.27	2.729	4.804	6.86	7.537	4.118
November	5.97	2.400	6.723	3.24	1.862	3.643	5.31	5.922	3.055
December	5.25	2.015	5.950	5.05	1.482	5.612	4.40	4.959	2.089

November.^[49] The east monsoon causes the dry season with high wind intensity. In Fig. 8, the east monsoon moves from the southeast.

From Table 5 and Fig. 9, in Papua, the effect of the west monsoon in December, January, and February gives an average wind speed of 5.25 m/s, 6.14 m/s, and 6.06 m/s. In the first transition, which is in March, April, and May, the average wind speed is 4.50 m/s, 5.00 m/s, and 7.00 m/s. The influence of the east monsoon in June, July, and August gave the highest average wind speeds of 8.99 m/s, 9.27 m/s, and 9.58 m/s. In the second transition, September, October, and November have average speeds of 8.40 m/s, 6.98 m/s, and 5.97 m/s. Table 5 shows the tendency of wind speed due to the influence of monsoon winds on wind speed in Maluku and Ujung Kulon, giving the same data trend.

4. Sensitivity analysis

The sensitivity analysis uses linear and non-linear regression methods to examine the relationship between turbine specifications-including cut-in speed, cut-off speed, and rated speed and key performance indicators such as capacity factor and energy cost. This analysis is tailored to the context of wind energy availability in Indonesia. Understanding these relationships is essential for optimizing turbine specification selection, ensuring that the chosen turbines perform efficiently and cost-effectively under the specific wind conditions found in the region.

4.1 Turbine data

The turbine used in this study is a horizontal-axis wind turbine (HAWT). In a HAWT, the rotor axis runs parallel to the ground and aligns with the direction of the wind. HAWTs are more sought after in the industry and preferred by investors over vertical-axis wind turbines (VAWTs).^[50] Horizontal-axis wind turbines (HAWTs) are noted for their superior efficiency in converting wind into electricity because they have larger rotor

diameters and higher tip speeds.^[51] They have established themselves as a reliable and extensively developed technology, widely deployed due to their scalability for utility-scale applications and increased energy production capacity.^[52] Overall, HAWTs are preferred over VAWTs for their ability to generate more energy efficiently across diverse wind conditions.^[53] The data obtained for the HAWT can be seen in the appendix. Turbine data is needed to determine the correlation between the critical components of the turbine and the total output power produced. 127 offshore wind turbine data will be used for sensitivity analysis (see Table S1). The offshore wind turbine data obtained are rated power, cut-in wind speed, rated wind speed, cut-off wind speed, rotor diameter, and hub height. Then, from the data obtained, the relationship between rated power and cut-in wind speed, rated power and rated wind speed, and rated power and cut-off wind speed will be analyzed using the regression method.

From Fig. 10, it can be seen that the cut-in speed range for rated power 1-10 MW is 2-4 m/s with an average value of 3.14 m/s where the distribution of cut-in values is random for each rated power. Meanwhile, for the rated speed range on the 1-10 MW turbines, the smallest rated speed value is 7.5 m/s, and an immense value is 15 m/s with an average value of 11.75 m/s. For the cut-off variation in the 1-10 MW turbines data obtained, a cut-off variation of 20-30 m/s is produced. Most manufacturers set the cut-off speed at 25 m/s. The relationship between rated power and cut-in speed, rated speed, and cut-off speed is contained in Fig. 10. The effect of rated power on cut-in speed from the data obtained has an R square value of 1.7435E-05, representing that rated power has no significant effect on cut-in speed. The effect of rated power on rated speed is that a decrease follows an increase in rated power in rated speed. However, it is insignificant because the value has an R square of 0.01478. Rated power affects cut-in speed; the cut-off value will increase after the increased rated power. R square of 0.09541 represents this. The unrelatedness between

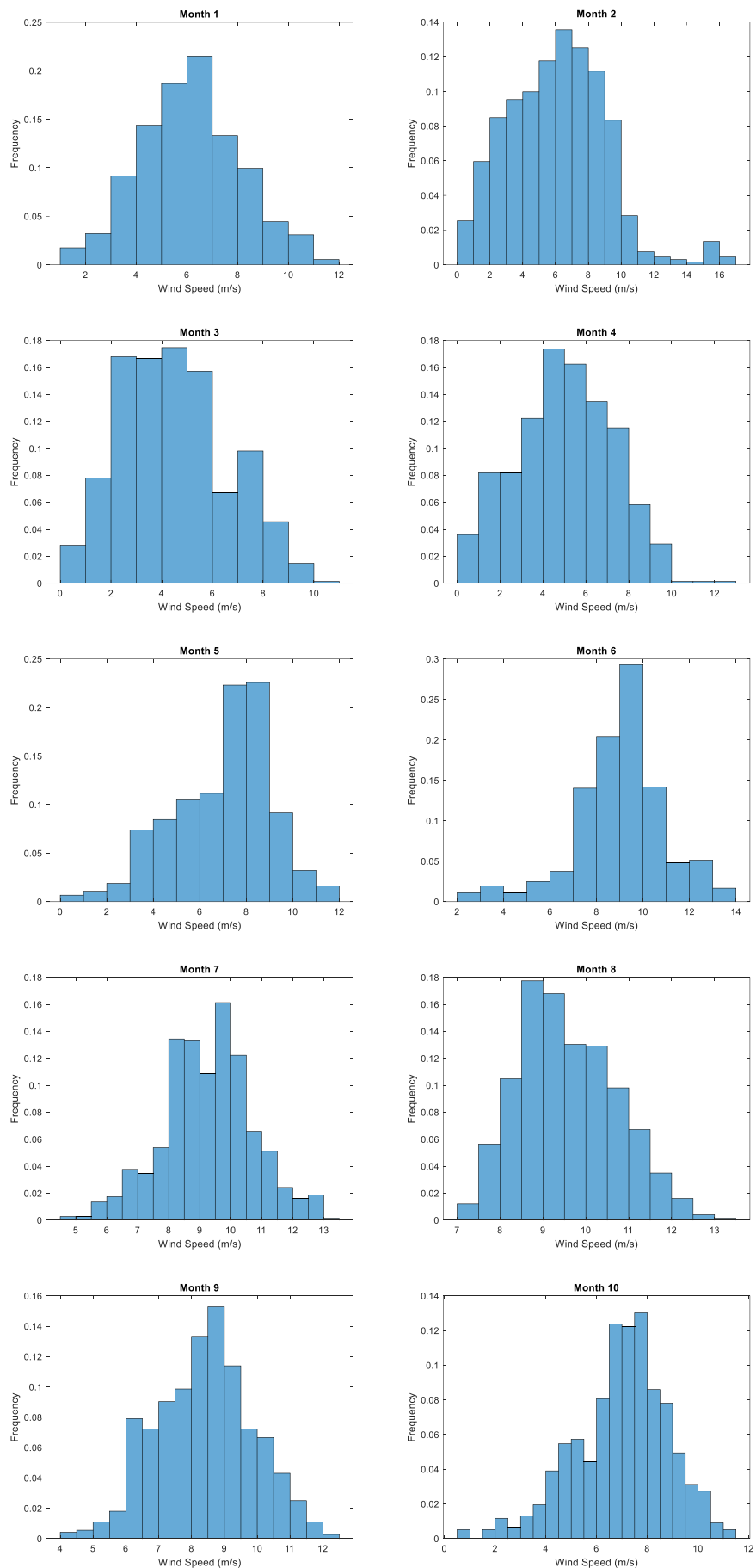


Fig. 9 Monthly wind speed distribution Papua.

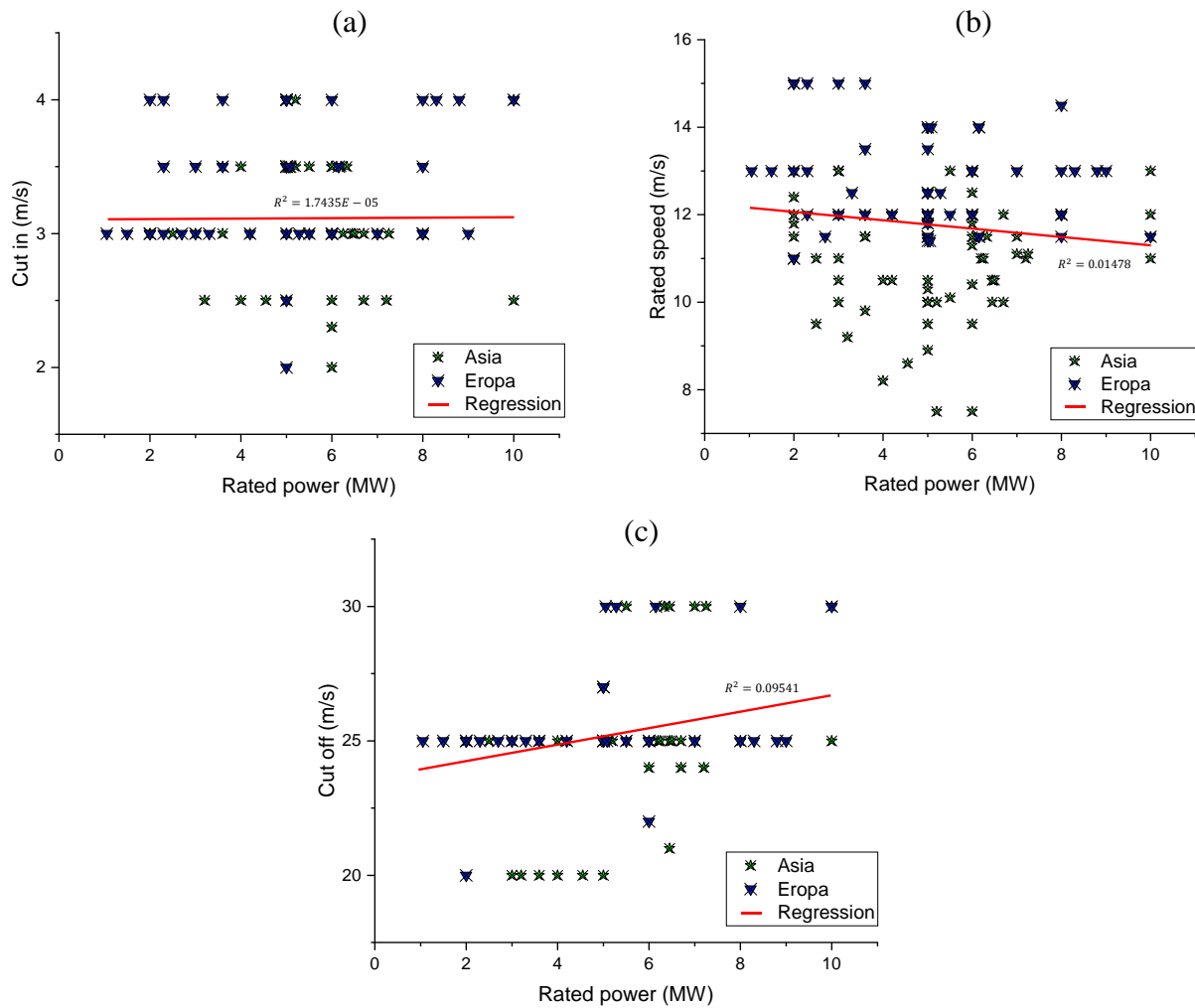


Fig. 10 (a) Rated power vs. cut-in speed, (b) Rated power vs. rated speed, (c) Rated power vs. cut-off speed.

variables is due to turbine manufacturing in each country's different characteristics. For example, turbines from Asia tend to have a lower cut-in speed and rated speed when compared to Europe at the same rated power value (see Fig. 10). This makes the data too random, and the R square value is minimal.

4.2 Case configurations

Since the relationship between rated power and cut-in speed, rated speed, and cut-off speed is non-constrained, the variation of each variable will be very accessible. In this case, variations are made to the cut-in speed, rated speed, and rated power. The variation (see Table S2) of cut-in speed is 2 to 4 m/s, the rated speed varies from 8 to 14 m/s, and the rated power varies from 1 to 10 MW. The outputs obtained are annual energy production, capacity factor, and cost of energy. Papua is the selected region to develop the sensitivity analysis. It is an area where the offshore wind resource is good, with an average wind speed of 6.94 m/s at 100 m. The cut-off speed is set with a value of 25 m/s.

The power curve calculating energy potential is obtained using the Betz limit discussed in Section 2.3. Using equation (8), a normalized power curve will be obtained to calculate potential energy. C_p follows the Betz limit of 0.593, and the

Area (πR^2) is assumed to be 1 m^2 , with wind speeds of 2 to 25 m/s. Table 6 details the normalization for each variation.

Figure 11 shows the relationship between cut-in speed with capacity factor and cost of energy. By using linear regression analysis, the relationship between variables can be obtained. From the graph, the variation in cut-in speed does not significantly affect the output capacity factor and cost of energy. The R square value for speed cut vs. CF is 2.12E-05. At the same time, the R square value for cut-in speed vs. COE is 1.27E-05.

Figure 12 shows the relationship between rated speed with capacity factor and cost of energy. From the graph, the variation of rated speed significantly affects the capacity factor, where a decrease follows the increase in rated speed in the capacity factor. This is because Papua's annual average wind speed is 6.94 m/s, so turbines with a low-rated speed have a significant capacity factor. Fig. 12(b) shows that an increase follows the increase in rated speed in COE. Following the economic analysis in Section 2.5, CF affects the COE value. CF at the highest rated speed gives the lowest value (see Fig 12(a)), so the resulting COE is more expensive. The R square value for the variation of rated speed against capacity factor is 0.9819, indicating more than 90% of the total

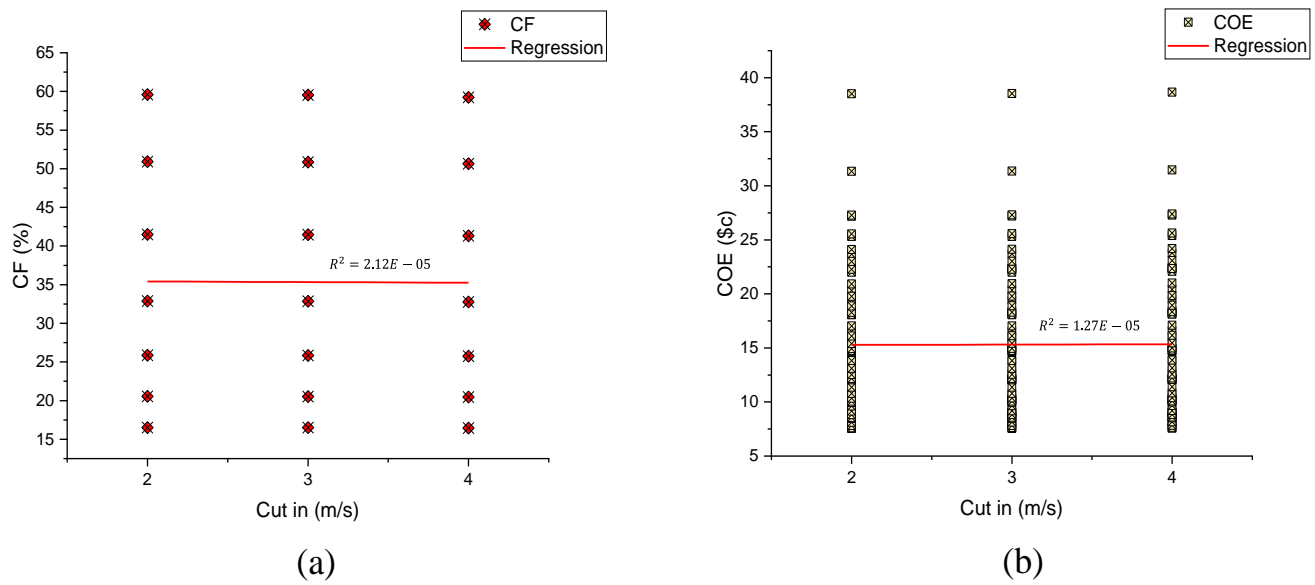


Fig. 11 (a) Cut-in speed vs. CF, (b) Cut-in speed vs. COE.

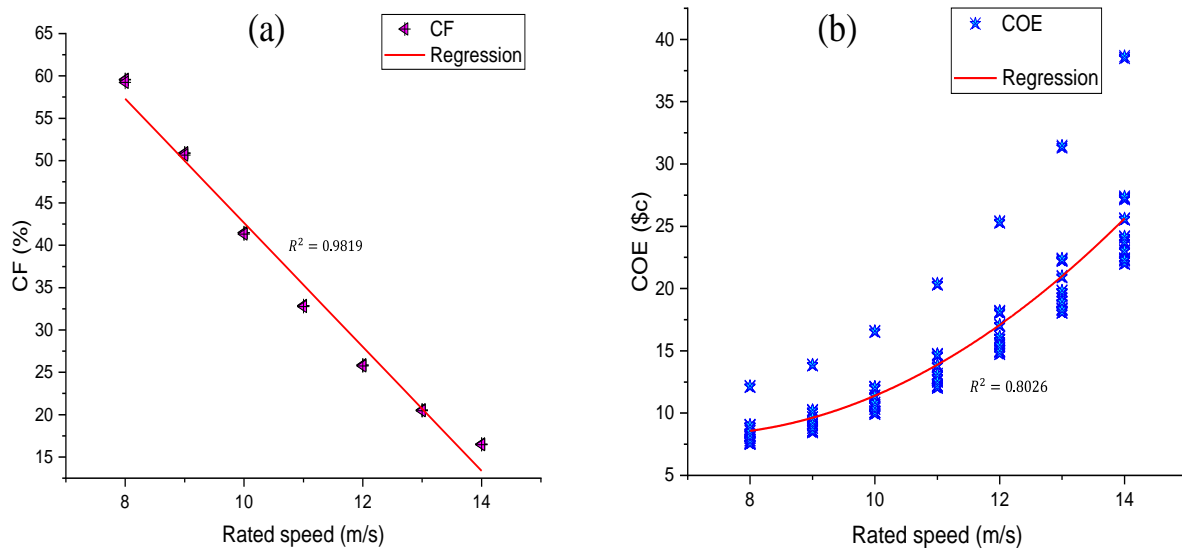


Fig. 12 (a) Rated speed vs. CF, (b) Rated speed vs. COE.

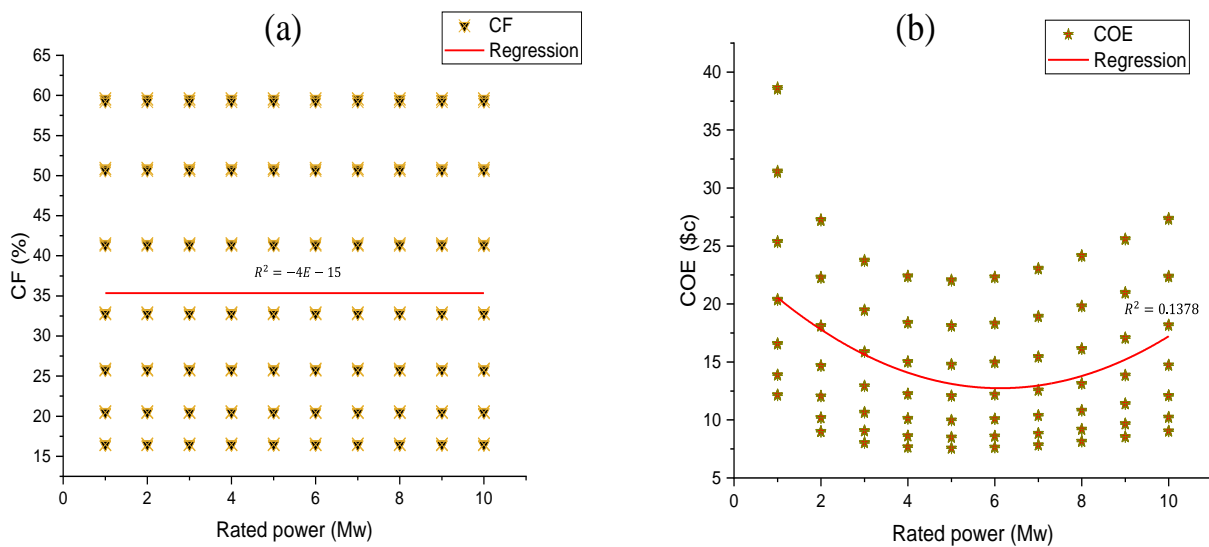


Fig. 13 (a) Rated power vs. CF, (b) Rated power vs. COE.

Table 6. Normalized power curve.

Wind Speed (m/s)	Normalized power curve at rated speed							
	8 m/s	9 m/s	10 m/s	11 m/s	12 m/s	13 m/s	14 m/s	
2	0.016	0.011	0.008	0.006	0.005	0.004	0.003	
3	0.053	0.037	0.027	0.020	0.016	0.012	0.010	
4	0.125	0.088	0.064	0.048	0.037	0.029	0.023	
5	0.244	0.171	0.125	0.094	0.072	0.057	0.046	
6	0.422	0.296	0.216	0.162	0.125	0.098	0.079	
7	0.670	0.471	0.343	0.258	0.198	0.156	0.125	
8	1.000	0.702	0.512	0.385	0.296	0.233	0.187	
9	1.000	1.000	0.729	0.548	0.422	0.332	0.266	
10	1.000	1.000	1.000	0.751	0.579	0.455	0.364	
11	1.000	1.000	1.000	1.000	0.770	0.606	0.485	
12	1.000	1.000	1.000	1.000	1.000	0.787	0.630	
13	1.000	1.000	1.000	1.000	1.000	1.000	0.801	
14	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
15	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
16	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
17	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
18	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
19	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
21	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
22	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
23	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
24	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
25	1.000	1.000	1.000	1.000	1.000	1.000	1.000	

variability in the response variable is accounted for by the predictor variables. The R square for rated speed vs. COE using polynomial regression is 0.8026. A considerable R square value (close to 1) indicates that the rated power correlates with the CF and COE outputs.

Figure 13 shows the relationship between the rated power capacity factor and the cost of energy. Linear regression is used for rated power vs. CF, and polynomial regression is used for rated power vs. COE. Since the normalization of the power curve is done using the rated power, the rated power does not affect the capacity factor (see Fig. 13 (a)). In Fig. 13(b), the energy cost will decrease until the rated power is 5 MW and then increase again after passing it. The R square for rated speed vs. CF using linear regression is $-4E-15$. Using polynomial regression, the R square value for rated speed vs.

COE is 0.1378.

From Figs. 12, 13, and 14, it can be concluded that the most impactful factor on capacity factor and cost of energy in this study is rated speed. The second factor is rated power. The most optimal rated power for wind distribution in Papua is 3 MW, 4 MW, and 5 MW. In this range, the COE value provides a low and stable value.

5. Electricity products

5.1 Offshore wind turbine model

Based on the sensitivity analysis discussed in the previous section (Section 4), a suitable wind turbine model for the target locations is a wind turbine with a rated power of 3 - 5 MW with a rated speed between 10 - 12 m/s. The 127-turbine data contained in the appendix (Table S1) and seven turbines were

Table 7. Specification of the selected offshore wind turbine.

Turbine ID	Rated Power (Mw)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-off speed (m/s)	Rotor diameter (m)	Hub height (m)
T ₁	3	3	12	25	113	100
T ₂	3	3	12	25	112	113
T ₃	3.6	3.5	11.5	25	122	90
T ₄	3.6	3.5	12	25	120	90
T ₅	3.6	3	12	25	116	90
T ₆	4	3.5	10.5	25	137	120
T ₇	5	4	11.5	25	128	120

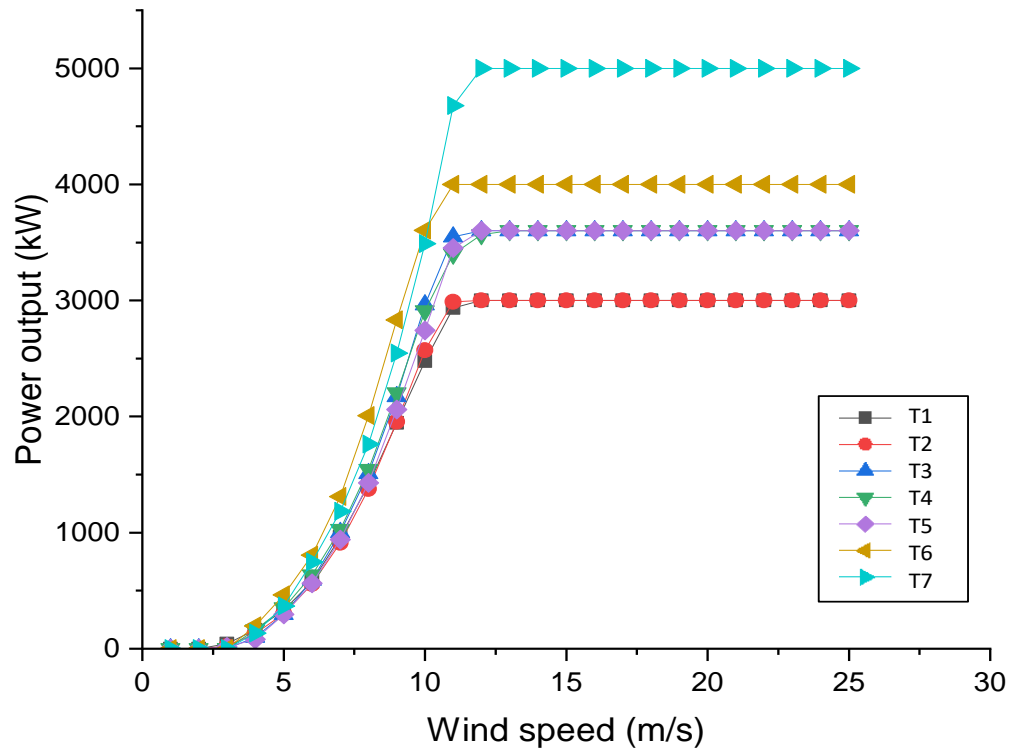


Fig. 14 Power curve model.^[54-59]

selected to be analyzed for their performance under Indonesian wind conditions (Table 7). All turbine performance is evaluated based on the hub height. Fig. 14 reveals the power curve of each system, identifiable throughout the cut-in speed, rated speed, and cut-off speed.

5.2 Annual energy production and capacity factor

The estimation of the AEP and CF is shown in Table 8, the value corresponding to a single wind turbine. The calculation results show that the turbine with ID T₆ has the most significant capacity factor for the three selected locations (Papua, Maluku, and Ujung Kulon). Using the turbine, Papua can generate 15268.14 MWh/year with a capacity factor of 39.11%. AEP in Maluku using the same turbine is 11555.17 MWh/year with a capacity factor of 29.60%. Meanwhile, the AEP in Ujung Kulon using a turbine with ID T₆ has the smallest value among the three locations at 9532.37

MWh/year with a CF of only 24.42%. The smallest AEP and CF values for the three locations are calculated using turbines with ID T₅. The Papua’s capacity factor is only 30.22%, with an AEP of 10617.41 MWh/year. This value is pretty good, considering the capacity factor for offshore wind turbines is in the range of 30 - 40%.^[60] Maluku has a lower capacity factor than Papua at 23.86, with an AEP of 8381.77 MWh/year for a single turbine. An even lower capacity factor is obtained in Ujung Kulon, which only reaches 19.10%, the lowest among the three. AEP in Ujung Kulon using a turbine with ID T₅ only reached 6711.20 MWh/year for a single turbine.

According to the results, the turbine with ID T₆ is most prominent by considering the capacity factor and annual energy production, corresponding to offshore sites most suitable for developing wind projects. T₆ is the most optimal turbine because it has the lowest rated speed of 10.5 m/s. Following the discussion in Section 4.2, rated power is a parameter significantly affecting the capacity factor. The

Table 8. Electricity products.

Turbine ID	Papua		Maluku		Ujung Kulon	
	AEP (MWh)	CF (%)	AEP (MWh)	CF (%)	AEP (MWh)	CF (%)
T ₁	10340.37	35.32	8098.96	27.66	6666.29	22.77
T ₂	10766.43	36.77	8155.58	27.85	6680.54	22.82
T ₃	11185.94	31.84	8809.42	25.07	7074.50	20.13
T ₄	11333.12	32.26	8961.52	25.51	7290.80	20.75
T ₅	10617.41	30.22	8381.77	23.86	6711.20	19.10
T ₆	15268.14	39.11	11555.17	29.60	9532.37	24.42
T ₇	14830.93	30.39	11142.49	22.83	8928.32	18.30

average wind speed in Indonesia, which is a speed of 6-7 m/s with a standard deviation of 2.5 (see Table 4), means that the wind distribution that often appears is the wind with a speed of 4.5-9.5 m/s. Fig. 14 shows that T₆ has the highest power output value for the wind range of 4.5-9.5 m/s. This also causes T₆ to have the highest capacity factor. Based on the results obtained, it can be concluded that offshore wind turbines with a cut-in speed of 2.5 - 4 m/s are suitable for the Papua, Maluku, and Ujung Kulon.

5.3 Economic assessment

The cost of energy (COE) is based on economic analysis in Section 2.5. Equations (13) and (14) are used to determine the cost of energy for each location. The results of the calculation will be compared with the local electricity tariff. In Indonesia, tariffs for renewable electricity production are based on a Power Purchase Agreement (PPA) between the power plant operator and the State Electricity Company (*Perusahaan Listrik Negara - PLN*), and the maximum electricity tariff is capped by the essential cost of electricity provision (*Biaya pokok produksi - BPP*).^[13] In 2021, MMER published Decree No. 169.K/HK.02/MEM.M/2021, which regulates the amount of BPP for each region in Indonesia. The local electricity tariffs for Papua, Maluku, and Ujung Kulon are shown in Tables (9-11). All selected offshore wind turbines are assumed to utilize a monopile-type platform for the cost of energy calculations. These structures are suitable for sites with a water depth ranging from 0 to 30 m.^[61] Table 4 shows the water depth of the three locations is the same at < 5m.

Based on the calculation in Table 9, the two turbines can generate profits of up to 32 %, namely T₂ and T₆. T₂ provides

the lowest electricity price of 10.10 \$/kWh, while T₆ produces an electricity price of 10.21 \$/kWh. Although T₆ has the highest capacity factor value of 39.11%, the turbine does not give the best value on the COE value. The rated power and turbine size are more significant than T₂. T₆ has a rated power of 4 MW with a rotor diameter of 137 m and a hub height of 120 m. Meanwhile, T₂ has a rated power of 3 MW with a smaller diameter size of 112 m and a hub height of 113 m. The difference causes T₆ to have a more expensive installation cost than T₂.

Meanwhile, turbine T₇ obtained the most expensive energy cost result. The turbine has a rated power of 5 MW and the second lowest capacity factor of 30.39 %. However, using turbines with ID T₇ is still arguably good because the energy cost is still lower than the local electricity tariff of 12.09 \$/kWh and can cut electricity prices by 19.50 %.

Based on the calculations in Table 10, the two turbines potentially generating the most significant profit are T₂ and T₁. T₂ provides the cheapest electricity price of 12.69 \$/kWh with a profit of 29.34 %, and T₁ generates an electricity price of 12.79 \$/kWh with a profit of 28.78 %. Both turbines have the same rated power of 3 MW with minor rotor diameter and hub height differences. T₆, with a rated power of 4 MW and the highest capacity factor of 29.60 %, is not in the top 2 positions in COE, indicating that the turbine is unsuitable for Maluku, which has a wind speed of around 6.05 m/s. However, the price offered is still reasonable at 12.85 \$/kWh. With a wind speed of 6.05 m/s, the suitable turbine has a rated power of 3 MW. Meanwhile, the most expensive energy cost was obtained with turbine T₇.

Table 11 shows the results of the calculation of the cost of

Table 9. Economic assessment for Papua.

Turbine ID	AEP (MWh)	CF (%)	COE (\$/kWh)	Local electricity tariff (\$/kWh) ^[47]	Profit (%)
T ₁	10340.37	35.32	10.45		30.42
T ₂	10766.43	36.77	10.10		32.75
T ₃	11185.94	31.84	11.42		23.96
T ₄	11333.12	32.26	11.22	15.02	25.29
T ₅	10617.41	30.22	11.70		22.10
T ₆	15268.14	39.11	10.21		32.02
T ₇	14830.93	30.39	12.09		19.50

Table 10. Economic assessment for Maluku.

Turbine ID	AEP (MWh)	CF (%)	COE (\$/kWh)	Local electricity tariff (\$/kWh) ^[47]	Profit (%)
T ₁	8098.96	27.66	12.79		28.78
T ₂	8155.58	27.85	12.69		29.34
T ₃	8809.42	25.07	13.96		22.27
T ₄	8961.52	25.51	13.66	17.96	23.94
T ₅	8381.77	23.86	14.28		20.48
T ₆	11555.17	29.60	12.85		28.45
T ₇	11142.49	22.83	15.43		14.08

Table 11. Economic assessment for Ujung Kulon.

Turbine ID	AEP (MWh)	CF (%)	COE (\$¢/kWh)	Local electricity tariff (\$¢/kWh) ^[47]	Profit (%)
T ₁	6666.29	22.77	15.11		-159.99
T ₂	6680.54	22.82	15.05		-159.02
T ₃	7074.50	20.13	16.89		-190.68
T ₄	7290.80	20.75	16.34	5.81	-181.17
T ₅	6711.20	19.10	17.34		-198.49
T ₆	9532.37	24.42	15.15		-160.77
T ₇	8928.32	18.30	18.76		-222.83

energy in Ujung Kulon from 7 selected turbines. Because Ujung Kulon has a local electricity tariff that is much cheaper than Papua and Maluku, which is only 5.81 \$¢/kWh, the use of offshore wind turbines is not suitable for implementation. Implementing offshore wind turbines can be an appealing alternative to the harvesting instrument in Indonesia, which has vast maritime territory, including uncertain inland water and wind resources, which are challenging to apply the micro-style of hydro-wind turbines and solar panels.^[62-70] To be more precise, attractiveness calculation for these turbine styles is invited to be near-future renewable energy research, especially for potential application in archipelago countries.

6. Conclusions

The importance and necessity of this work are rooted in Indonesia's critical need for sustainable energy solutions. This country grapples with a significant reliance on fossil fuels and faces challenges in energy distribution due to its archipelagic geography. Offshore wind turbines offer a promising alternative to bridge the electrification gap, particularly in remote regions. In this study, we employed a comprehensive methodology that integrates wind data analysis using the Weibull distribution, sensitivity analysis for turbine selection, and economic feasibility assessments through metrics such as Annual Energy Production (AEP), Capacity Factor (CF), and Levelized Cost of Energy (LCOE). Our innovative approach included a detailed site selection process, considering technical and economic criteria to identify the most suitable locations for offshore wind projects.

The results show that Papua, Maluku, and Ujung Kulon are potential locations for offshore wind projects. The average wind speeds in Papua, Maluku, and Ujung Kulon were 6.94 m/s, 6.05 m/s, and 5.66 m/s at 100 m height. The wind characteristics for the three locations have the same trend: the mostly high-velocity wind blows from 130° (southeast).

Through sensitivity analysis, optimization indicates that for Indonesia's average wind speeds, the most suitable turbine features a cut-in speed of 2-4 m/s, a rated speed of 10-12 m/s, and a rated power of 3-5 MW. Papua, with its highest average wind speed of 6.94 m/s, stands out for achieving the most extensive Annual Energy Production (AEP) and Capacity Factor (CF), coupled with the lowest Cost of Energy (COE). Conversely, Ujung Kulon is deemed unsuitable for offshore wind projects due to its lower local electricity tariff than

offshore wind-generated electricity.

This work underscores the viability and benefits of offshore wind energy by addressing the geographical and economic challenges. Implementing offshore wind turbines in these selected regions could support Indonesia's commitment to achieving net zero emissions by 2060 and offer a cost-effective and environmentally friendly energy solution. This study provides a robust framework for future renewable energy projects in Indonesia's remote regions, highlighting the critical role of offshore wind energy in the country's sustainable energy transition.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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