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Research Article

Utility-scale wind power generation potential in low-wind regions: Insights for achieving the sustainable energy transition in developing countries

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Abstract. Wind energy represents a promising resource for accelerating the transition to renewable energy and meeting global net-zero emission targets. While wind turbines have generated considerable amounts of electricity in specific regions of four-season countries, their potential in low-wind countries is generally limited, thereby inhibiting further investigation. However, advancements in wind turbine design and wind resource databases have provided new opportunities for assessing utility-scale wind energy potential. Therefore, this study assessed the potential for utility-scale wind power generation in low-wind regions of Indonesia's Java–Bali region. The Weibull distribution of wind speed and theoretical energy output were investigated using 10-year hourly temporal-based wind speed data collected at 100 m height from 2006 to 2015. The National Renewable Energy Laboratory (NREL) power density classification was used to identify locations for energy generation analysis under wind turbine capacities of 1, 2, and 2.5 MW. The trade-offs between the average energy output over ten years and capacity factors were also considered. The results showed that the Ujungjaya area in Pandeglang Regency, Banten Province, has the potential to produce an estimated 13,916 MWh of energy per year using the 2.5 MW turbine with a capacity factor of 60.5% and Weibull parameters *k* and c of 2.49 and 8.22, respectively. The annual wind-based electricity generation potential of selected locations revealed that low-wind regions of Indonesia should not be overlooked when strategically planning wind energy utilisation to support the sustainable energy transition. In addition, the results have important implications for including additional wind energy in the energy mix of developing countries with similar low-wind regimes.

Keywords: Indonesia, renewable energy, Weibull distribution, wind-based electricity

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1. Introduction

Population growth and industrial infrastructure expansion are driving the demand for electricity in developing nations (Arnob *et al.,* 2023). Given the overuse of fossil fuels, which increases carbon emissions, developing nations must assess and execute energy transition strategies as efficiently as possible to meet the target of Sustainable Development Goal 7 (Babayomi *et al.*, 2022; Falcone, 2023; Wang & Lo, 2021; Frimpong *et al.*, 2025). Due to various technological and financial constraints, these countries have faced significant obstacles in deploying utility-scale renewable energy power plants. In addition, efforts to increase the reliability of the power grid in these countries are underway (Meegahapola *et al.*, 2021; Johannsen *et al.*, 2020; Bakht *et al.*, 2022; Malik *et al.*, 2022; Wali *et al.*, 2023).

In addition to solar power, wind energy is considered one of the most promising renewable energy resources for accelerating the energy transition needed to achieve global net-zero emission targets. In 2024, the worldwide installed capacity for onshore and offshore wind turbines amounted to 1,053 GW and 79.4 GW, respectively (IRENA, 2025). Although wind turbines have been a major source of electricity in some four-season countries, such as in Europe, the potential of wind energy in low-wind countries is very small, which has hindered further exploration.

Innovations in wind turbine technology and improvements in wind resource databases have paved the way for reevaluating the utility-scale wind energy potential of low-wind regions (Tan *et al.*, 2022; Shawket & Danook, 2025). Access to complete wind resource data can lead to breakthrough discoveries on wind spatial and temporal characteristics, which in turn may generate recommendations on wind turbine height (Liu *et al.*, 2019), wind resource potential identification methods (Feng *et al.*, 2019), wind turbine layout optimisation (Lu *et al.*, 2025), wind speed variation analyses (Yang *et al.*, 2024), and wind power density forecasts (Jiang *et al.*, 2025).

A study on wind energy generation in low-speed regions analysed the wind energy characteristics and potential using advanced turbine technologies in low-wind areas (Martin *et al.*, 2020), generated a histogram of the hourly wind speed data from different locations in Florida, United States, and identified three different wind speed pattern shapes. Another study

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conducted a comparative analysis of numerical and metaheuristic optimisations to identify the wind energy potential in low-wind areas of China (Jiang *et al.*, 2017).

Research on wind turbine design for low-wind environments has led to the development and evaluation of enhanced micro wind turbine blades. A comparison of these enhanced blades with existing commercial options in terms of cost and energy output in low-wind areas of Abu Dhabi and Al Ain, UAE, revealed that the new designs are significantly less expensive and produce more energy (Akour *et al.*, 2018). Another study on microscale wind turbine design analysed the aerodynamics and optimisation of the blades (Pourrajabian *et al.*, 2014). Meanwhile, a new airfoil design for rotor blades was proposed to enhance large horizontal-axis wind turbines in low-wind-speed regions (Li *et al., 2*020). Studies have also modified high-wind-speed turbine blades for low-wind applications (Yang *et al.*, 2019). Wind turbine aerodynamics and technologies for urban and rural low-wind areas have also been analysed to determine their technical viability and contrasted in terms of their effects on vibration, noise, spatial factors (Tan *et al.*, 2022; Wilberforce *et al.*, 2023), and determine whether high-power output can be produced at low-wind speeds (Suresh and Rajakumar, 2020).

Methodological studies have focused on increasing the production of wind energy in low-wind-speed areas, such as in Iraq (Darwish *et al.*, 2019), based on a wind energy optimisation iteration process at different heights to reveal the Weibull parameters, capacity factors, and computer-aided rotor design size. Another study performed a case study in Africa to analyse the effect of low-wind-speed periods on the reliability of wind energy systems (Seyedhashemi *et al.*, 2021) and revealed that flexibility could offer a solution to reducing the lack of reliability of wind-powered systems.

Recent research shows that turbine technology for low-wind areas is increasingly relying on very large rotors (≥150 m), low-specific-power designs, and new control strategies, such as individual pitch control, variable-speed operation, and wake steering (Simley *et al.*, 2024; Swisher *et al.*, 2022; Frutuoso *et al.*, 2025). These technologies are used to increase the energy captured and lessen the structural loads that occur at weak and highly variable wind speeds.

Numerical and probabilistic methods have also been used to increase and optimise the wind power output. These include Weibull analysis and mechanical adjustment optimisation of turbine blades in large as well as micro wind turbines. Nonetheless, the potential wind power generation in low-wind-speed areas of developing countries in tropical regions is poorly understood, thus representing an important research gap. Such countries and territories exhibit a similar spatial structure that prevents the accumulation of sufficient wind resources. Moreover, only a few studies have explored whether long-term wind speed data can be used to evaluate the potential of the utility-scale wind energy in these low-wind-speed jurisdictions.

While the Weibull distribution and National Renewable Energy Laboratory (NREL) wind power density classification are well-established and widely used methods, their application to long-term (10-year), high-resolution (hourly), 100 m wind datasets across multiple sites in equatorial Southeast Asia remains limited. Therefore, our study systematically applied these standardised methods to a long-term, high-resolution dataset (10 years, hourly resolution) across ten 100-metre height sites in a region that remains underrepresented in the utility-scale wind energy literature.

Moreover, this study performs a case study of the tropical Java–Bali region of Indonesia to spatially and temporally characterise the wind regimes in this region and evaluate the potential of utility-scale wind power generation in low-wind speed regions. Commercially available 1 MW, 2 MW, and 2.5 MW wind turbines were used to calculate the Weibull-based estimated energy generation and capacity factors from specific sites. Rather than assessing the newest technological advancements, this study evaluated 1–2.5 MW turbines because they represent commercially viable and bankable technologies that are easily accessible for developing markets such as Indonesia. Accordingly, the results can be immediately applied to deployment scenarios in the near future and serve as a benchmark for assessing upcoming ultra-large rotor technologies.

This study integrates long-term Weibull analysis, diurnal and seasonal variability assessments, wind rose diagrams, wind power curves, and comparative spatial characterisations across multiple coastal and inland sites to generate a regionally consistent wind resource baseline for equatorial low-wind regimes. This combination has not been previously reported for the Java–Bali wind energy context.

This study contributes to the renewable energy literature by establishing a long-term and multi-site high-resolution wind speed dataset for Java–Bali, quantifying the temporal and spatial variability under low-wind regimes, and demonstrating how modern turbine design interacts with tropical wind characteristics. Of note, the introduction of new methods for wind resource assessment is beyond the scope of the study.

2. Overview of Wind Power Generation in Indonesia

The estimated wind energy potential of Indonesia is 155 GW, which consists of 60.6 GW onshore and 94.2 GW offshore (IESR, 2022). Areas with typical potential onshore wind speeds of 6-8 m/s are found along the southern coast of Java, South Sulawesi, Maluku, and Nusa Tenggara (Cendrawati *et al.*, 2023). The total technical potential of wind turbine capacity at a 100-metre hub height in the Java–Bali region is estimated at approximately 0.83–12.5 GW (IESR, 2021). Utility-scale wind power has contributed to Indonesia's national power grid since 2018, and the capacity is approximately 157 MW, mainly from two utility-scale wind farms located in South Sulawesi Province: the 75 MW Sidrap wind project and the 72 MW Tolo/Jeneponto wind farm (Kusuma *et al.*, 2024; Pambudi *et al.*, 2025). Pioneering projects with an installed capacity of approximately 720 kW have emerged in Nusa Penida, Bali (Kumara *et al.*, 2014). However, their operation has been reported to be discontinued due to equipment degradation (Setiawan *et al.*, 2016). The current campaign for the island of Bali is a 100% renewable energy mix dominated by solar photovoltaics (PV), mini hydro systems, and a total wind turbine capacity of 40 MW, as reported in the project pipeline (Global Energy Monitor Wiki, 2025).

The more ambitious goal of 5 GW of wind has been set by the Indonesian government (Reccessary, 2024). The Minister of Energy and Mineral Resources (MEMR) Regulation No. 5/2025 (EBT PPA) has updated the pricing/contracting scheme, while a new local content (TKDN) regime was expected to relax the

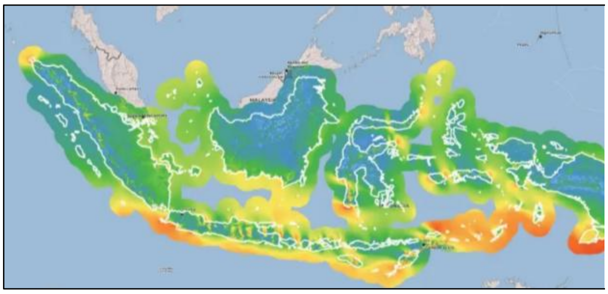

Fig 1. Indonesia's Global Wind Atlas mean wind speed map at 100 m

current requirements for wind power projects starting in July 2024. The goal of these changes is to make wind energy projects more financially viable (ACE, 2025; JETP Indonesia, 2024).

The wind resources in the Java–Bali area do not appear to be as promising as those in South Sulawesi or East Nusa Tenggara. However, potential still exists along the southern coast and in some inland areas, from Banten, southern West Java, to southern East Java, as well as spots in Bali. A preliminary report (MEMR, 2024) identified several pre-feasibility onshore projects in Java. Figure 1 depicts Indonesia's mean wind speed at 100 m, as obtained from the Global Wind Atlas (Global Wind Atlas, 2025).

3. Methodology

This study performed a case study to evaluate the potential for wind electricity generation in Java–Bali, Indonesia. Locations for further evaluation were determined based on long-term hourly temporal-based wind speed data from 2006 to 2015 (10 years) for several locations in the Java–Bali area and a power density-based approach. The approach included technical parameters associated with wind energy, such as Weibull distribution parameters, theoretical annual electricity generation, wind rose diagrams, power curve analysis, and capacity factors. The primary goal of this research is to establish a climatological baseline for equatorial low-wind regimes rather than to capture recent interannual climate trends.

The analysis began by visually inspecting the Java–Bali map on the Global Wind Atlas website, which shows the average wind speed at a height of 100 metres. In this stage, up to 20 locations marked in orange to red were selected that have a mean wind speed of 5 m/s or higher and may have a high potential for wind energy production. The 20 locations were spread throughout the Java–Bali area. Figure 2 depicts the 20 selected locations, while Table 1 lists all locations, including their geographical coordinates and 10-year average hourly wind speeds.

The wind speed dataset was obtained from the Indonesia Wind Prospecting website (https://www.windprospecting.com/) and can be accessed upon request at https://drive.google.com/drive/folders/19_bTRPzCUEAtuyYzwqI1smsPhbc3ImHd? usp=sharing.

The wind-class classification used in this study was based on the wind power density from the NREL. Within the classification, only sites in "fair" or "marginal" wind classes were considered for this study. The wind power density value was determined according to Equation 1 (Aldaoudeyeh & Alzaareer, 2020), while the NREL wind-class classification based on the wind power density and wind speed at 100 m is presented in Table 2.

$$P_D = \frac{1}{2}\,\rho\,v^3 \qquad (1)$$

Fig 2. All 20 sites designated in the Global Wind Atlas for utility-scale wind power generation in the Java–Bali region, Indonesia

Table 1
Selected locations (sites, regencies/cities, provinces), coordinates, and 10-year average hourly wind speed in the Java–Bali region, Indonesia

No.	Locations	Lat (S); Lon (E)	10-year average hourly wind speed (m/s)
1	Ujungjaya, Pandeglang, Banten	6.835; 105.231	7.30
2	Tamanjaya, Pandeglang, Banten	6.781; 105.501	6.76
3	Ujung Genteng, Sukabumi, West Java	7.348; 106.419	6.76
4	Sancang, Garut, West Java	7.726; 107.850	5.87
5	Panongan, Cirebon, West Java	6.862; 108.579	5.97
6	Patimban, Subang, West Java	6.214; 107.877	5.23
7	Cengal, Majalengka, West Java	6.916; 108.228	6.22
8	Purwodadi, Gunung Kidul, Yogyakarta	8.131; 110.685	6.18
9	Sluke Manggar, Rembang, Central Java	6.619; 111.495	5.45
10	Ujungwatu, Jepara, Central Java	6.403; 110.928	5.81
11	Berahan Kulon, Demak, Central Java	6.754; 110.577	5.31
12	Pruwatan, Brebes, Central Java	7.294; 108.984	6.03
13	Tugurejo, Ponorogo, East Java	7.969; 111.549	6.21
14	Wates Kulon, Lumajang, East Java	7.915; 113.223	7.08
15	Sumberwaru, Situbondo, East Java	7.834; 114.438	6.35
16	Wongsorejo, Banyuwangi, East Java	7.996; 114.438	6.52
17	Tiron, Kediri, East Java	7.780; 111.954	6.25
18	Sumber Klampok, Buleleng, Bali	8.104; 111.954	6.08
19	Bunutan, Karang Asem,Bali	8.375; 115.707	5.71
20	Pecatu, Badung,Bali	8.833; 115.113	5.02

Table 2
NREL wind-class classification based on the wind power density and wind speed at 100 m (Girleanu *et al.*, 2021).

Wind Class	100 m reference height	
	Power density (W/m^2)	Wind Speed (m/s)
C1 (poor)	< 260	< 6.1
C2 (marginal)	260–420	6.1–7.1
C3 (fair)	420–560	7.1–7.8
C4 (good)	560–670	7.8–8.3
C5 (excellent)	670–820	8.3–8.9
C6 (outstanding)	820–1,060	8.9–9.7
C7 (superb)	> 1,060	> 9.7

where P_D is the wind power density (W/m²), ρ is the air density (kg/m³), with an assumed value of 1.225 kg/m³; and v is the mean wind speed (m/s).

The wind speed distributions were modelled using the Weibull distribution, and its main parameters, i.e., the shape parameter (k) and scale parameter (c), were calculated using the Justus estimation method. Parameters k and c represent wind variability and characteristic wind speed, respectively. Winds with k values less than 2 are highly changeable and gusty, while those with k values from 1.8 to 2.5 are generally stable. The probability density function of the Weibull distribution was formulated in Equations 2–4 as follows.

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{2}$$

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

$$c = v_m \left(0.568 + \frac{0.433}{k}\right)^{-\frac{1}{k}} \tag{4}$$

where $f(v)$ is the Weibull probability density function; k is the Weibull shape factor; c is the Weibull scale factor; v_m is the mean wind speed (m/s); and σ is the wind speed standard deviation (m/s).

The Weibull distribution function can also be used analytically to calculate capacity factors (CFs). These factors integrate the Weibull probability function across the turbine's operating speed range at the turbine's nominal speed. A high CF value indicates that most wind speeds at that location are within the turbine's effective operating range, thus allowing for maximum energy efficiency. The CF equation for the Weibull distribution is presented in Equation 5 (Ismail *et al.*, 2020), while the annual energy generated is calculated based on the wind turbine's power curves according to Equation 6 (NREL, 2014).

$$CF = \frac{e^{-\left(\frac{V_c}{c}\right)^k} - e^{-\left(\frac{V_R}{c}\right)^k}}{\left(\frac{V_R}{c}\right)^k - \left(\frac{V_c}{c}\right)^k} - e^{-\left(\frac{V_f}{c}\right)^k} \tag{5}$$

$$E_{yearly} = \sum_{i=1}^{n} P(v_i) \cdot t(v_i) \tag{6}$$

where CF represents the capacity factor; V_c is the cut-in wind speed; V_R is the rated power wind speed; V_f is the furling wind speed; e is the Euler constant, which has an approximate value of 2.718; E_{yearly} is the total annual electricity generation (kWh); $P(v_i)$ is the turbine power output (Watts) at wind speed v_i, as determined by the turbine's power curve; $t(v_i)$ is the period (hours per year) at wind speed v_i; v_m is the mean wind speed (m/s); and n is the number of bins/wind speed classes (commonly at 1 m/s intervals).

Since this study prioritises commercially deployable turbine classes to ensure that the results are immediately applicable to policies and planning, it assesses the potential of wind energy generation by employing three commercially available Horizontal Axis Wind Turbine (HAWT) models with power outputs of 1 MW (Leitwind LTW90/1000), 2 MW (Sany SE125/2000), and 2.5 MW (Sany SE145/2500), which are presented in Table 3 along with their essential specifications.

As presented in Table 3, the selected turbines are suitable for low-wind power density (low-specific-power) because they present characteristics of low-wind-optimised turbines with a large-rotor area. The LTW90 turbines, including the LTW90/1000, for example, are marketed specifically for low-wind and community applications. A 90 m rotor diameter results in a large swept area for a 1 MW rating (low-specific-power); therefore, such turbines are well-suited to sites with mean wind speeds of 6–7 m/s, resulting in good energy capture at low speeds and a relatively high annual energy production per rated kW. Sany's 2 MW SE125 variant has a larger rotor and produces relatively low-specific-power when compared to older 2 MW turbines. This variant should be suitable for small wind farms (2–10 turbines) located in areas with moderately high wind power densities. Meanwhile, Sany 2.5 MW turbines with rotors up to 145 m have a large swept area and low-specific-power and thus are ideal for low-wind conditions.

In addition to wind speed data, this research also considered wind direction data at certain high-potential sites to improve the technical relevance of the wind resource assessment. To help understand the prevailing wind directions and frequency of different wind speeds, this work constructed wind roses at several top-tier locations. Although detailed wake modelling or layout optimisation was not performed, the use of wind roses elevates the current assessment beyond the theoretical potential to provide a more technically justified pre-feasibility evaluation of wind energy deployment in the Java–Bali region.

Finally, this research also established a quantitative rank of locations that involves a weighted score combining energy and CF. The rank could be helpful for decision makers by directly allowing them to pick the "best overall site and turbine

Table 3
Selected wind turbines (HAWT) and their specifications

Wind Turbine	Hub Height (m)	Cut-in Speed (m/s)	Rated Speed (m/s)	Cut-out Speed (m/s)	Rotor Diameter (m)
Leitwind LTW90/ 1000 (WT-1)	105	3	9	25	90
Sany SE125/ 2000 (WT-2)	90	2.5	8.5	22	125
Sany SE145/ 2500 (WT-3)	100	3	8.2	22	145

combination" from three available schemes. These include a balanced score of 50% energy – 50% CF (namely Scheme 1: E50-CF50), as well as alternatives of 70% energy – 30% CF (namely Scheme 2: E70-CF30) and 30% energy – 70% CF (namely Scheme 3: E30-CF70).

4. Results and Discussion

The wind power density evaluation of the 20 sites revealed that only 11 sites qualified for the two lowest "fair" and "marginal" wind class categories, while none of the sites qualified for the "good" category. Table 4 presents the 10-year (2006–2015) average hourly wind power density for all locations that belong to "fair" and "marginal" wind classes in descending order of power density values, along with their Weibull parameters (*k* and *c*).

All 11 "fair" and "marginal" wind class locations were situated in Banten (1, 2), West Java (3, 5, 7), East Java (13, 14, 15, 16, 17), and Bali (18). While most were coastal sites, two were located in the island's interior. Sumber Klampok, Buleleng, had the lowest 10-year wind power density at 268.4 W/m2, while Wates Kulon had the highest at 450.9 W/m2. Moreover, seven of the sites featured outstanding 10-year average hourly power densities of 300 W/m2 or more. A 300 W/m wind power density is typically considered adequate for utility-scale modern wind turbines that usually have hub heights of approximately 100 m (Hodel et al., 2024). This wind power density has been adopted as the industry benchmark for assessing wind potential.

Based on the Weibull parameters calculation, Ujungjaya in Pandeglang (2.49) and Ujung Genteng in Sukabumi (2.54) both had *k* values of approximately 2. Similar *k* values were observed in the top-tier locations because wind turbines can produce more energy and have lower fatigue loads when the wind is constant. Ujungjaya had the highest *c* value (greater wind power density) of the 11 locations at 8.22, followed by Wates Kulon (7.96) and Ujung Genteng (7.62). These sites exhibit the greatest potential for wind energy. Meanwhile, Wates Kulon had an extremely low *k* value despite the high wind speeds.

Long-term 10-year data for wind speed (*v*) and *k* and *c* values enable comparative evaluations of site quality. The 11 locations in Table 4 can be divided into three categories: top-tier sites (high mean speed and stable distribution), mid-tier sites (adequate wind speeds but more variable), and lower-tier sites. The top-tier sites were Ujungjaya (high *v*, *k*, and *c*), Ujung Genteng (good balance of wind speed and stability), and Wates Kulon (strong winds but moderate stability). Wongsorejo and Cengal represented ideal mid-tier sites based on their good *v* but low *k* values. Low-tier sites, such as Panongan in Cirebon, exhibited low *v* and *c* values.

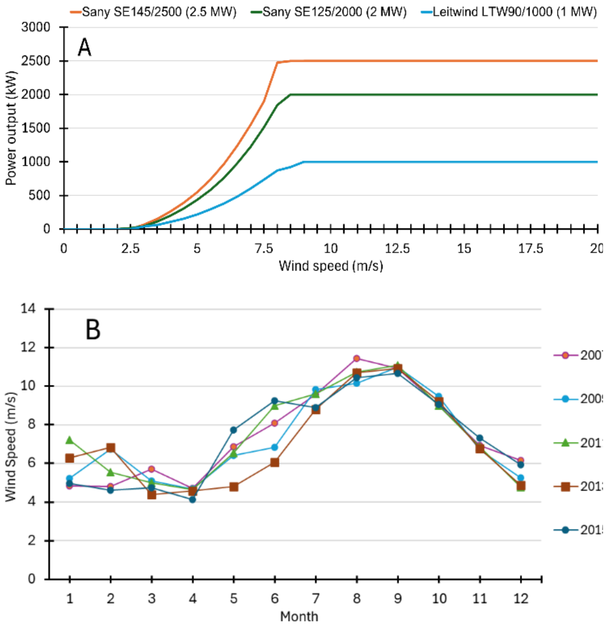

Fig 3. Power curves of the assessed wind turbine models (graph A), and average wind speeds by month (seasonal) from 2007 to 2015 (2-year intervals) for Ujungjaya (graph B).

Figure 3 (graph A and graph B) depicts the power curves of the assessed wind turbine models and average wind speeds by month (seasonal) from 2007 to 2015 (2-year intervals) for Ujungjaya, respectively. Figure 3 (graph A) shows a crucial slope between 4 and 6 m/s of the power curve. The steepest curve was observed for WT-3 (Sany SE145/2500), meaning that this model produced the most energy at low to medium wind regimes. Although this model was similar to WT-2, it exhibited a lower capacity output. In contrast, WT-1 (LTW90/1000) exhibited the most gradual slope and thus generated the least amount of energy in locations with moderate winds.

In graph B, the wind speeds averaged 4 to 6 m/s from January to April, whereas from May onward, a significant increase was observed. The strongest winds occurred in the middle of the year, particularly from July to September, when the change in wind speed was stable at approximately 10 m/s and occasionally reached 11 to 12 m/s. Following September, the wind gradually decreased until the end of the year. Monsoon winds were primarily responsible for the changes in the wind speed throughout the year, as well as the timing of the seasonal peak,

Table 4

Ten-year (2006-2015) average hourly wind power density and Weibull distribution parameters (*k* and *c*) at selected locations with fair and marginal wind classes

Loc No.	Locations	10-year power density (W/m^2)	NREL wind class	*k*	*c*
14	Wates Kulon, Lumajang	450.9	Fair	1.77	7.96
16	Wongsorejo, Banyuwangi	397.1	Marginal	1.60	7.28
7	Cengal, Majalengka	377.1	Marginal	1.51	6.90
1	Ujungjaya, Pandeglang	369.9	Marginal	2.49	8.22
15	Sumberwaru, Situbondo	330.3	Marginal	1.79	7.14
2	Tamanjaya, Pandeglang	307.5	Marginal	2.37	7.63
5	Panongan, Cirebon	302.7	Marginal	1.64	6.68
17	Tiron, Kediri	297.8	Marginal	1.84	7.04
3	Ujung Genteng, Sukabumi	289.3	Marginal	2.54	7.62
13	Tugurejo, Ponorogo	285.3	Marginal	1.87	6.99
18	Sumber Klampok, Buleleng	268.4	Marginal	1.89	6.86

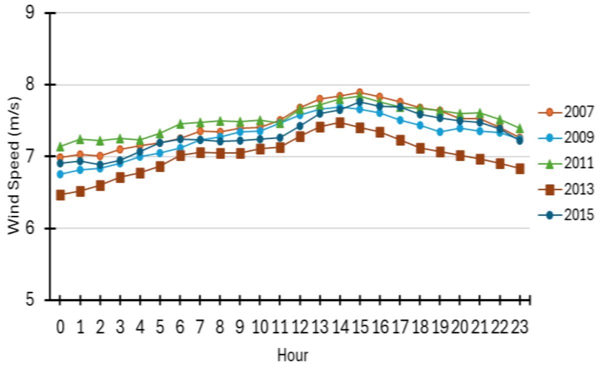

Fig 4. Average wind speeds by hour of the day (diurnal) from 2007 to 2015 (2-year intervals) for Ujungjaya

which was consistent and demonstrated the strength of the monsoon-driven winds.

Figure 4 shows the diurnal pattern of wind speeds at Ujungjaya over 2-year intervals from 2007 to 2015. Wind speeds started to rise slowly from early morning and reached their maximum in the early to mid-afternoon (13:00 to 15:00), with average values mostly between 7.4 and 7.9 m/s. After the peak, the wind speeds decreased in the evening and at night. The diurnal patterns shown in Figure 4 also reveal that although the absolute wind speed levels changed from one year to another, the time when the peak occurred, and its shape were generally consistent. Daily variation patterns provide important data for the integration of utility-scale wind power into the grid by revealing the best times for power generation.

Figure 5 presents a ten-year Weibull PDF overlaid with the actual 10-year hourly wind speed frequency histogram for Ujungjaya, Pandeglang (graph A); a ten-year Weibull PDF overlaid with the actual 10-year hourly wind speed frequency histogram for Panongan, Cirebon (graph B); and power curves of all wind turbines overlaid with the wind speed distribution for Ujungjaya (graph C).

A 10-year Weibull probability density function graph, which is overlaid with actual hourly wind speed histograms, is used to identify the various wind regimes. Ujungjaya in Pandeglang and Panongan in Cirebon are shown as they are considered the best and worst locations, respectively. Figure 5 (graph A) shows that Ujungjaya has a wider distribution across higher wind speeds (5 to 12.5 m/s), implying that it has stronger winds that can be used to generate electricity; moreover, the Weibull model is appropriate. In contrast, Panongan's distribution is characterised by low-wind speeds and a decline in frequency after 7.5 m/s; thus, the energy potential is severely limited (see Figure 5 graph B). Meanwhile, Figure 5 (graph C) provides insights into the influence of local wind conditions in Ujungjaya on the performance of different turbine output capacities and the operating region of each turbine. The results show that the 2.5 MW turbine would yield the maximum expected energy output. As mentioned in the methodology section, this study applied wind roses to analyse the frequency of wind directions over a particular year. Figure 6 depicts the wind roses at the top-tier sites, such as Ujungjaya, Ujung Genteng, and Wates Kulon.

The wind patterns at Ujungjaya (charts A and B) remained stable for nearly a decade. In both 2006 and 2015, the wind was primarily from the southeast (55% to 60% of the time). In terms of speed, both charts show large blocks of green (winds 10 m/s or higher) and blue (7.5 to 10 m/s). This indicates that the wind was strong and almost always from the southeast. Across the three different locations in 2015 (charts A, C, and D), local geography has a significant influence on wind behaviour.

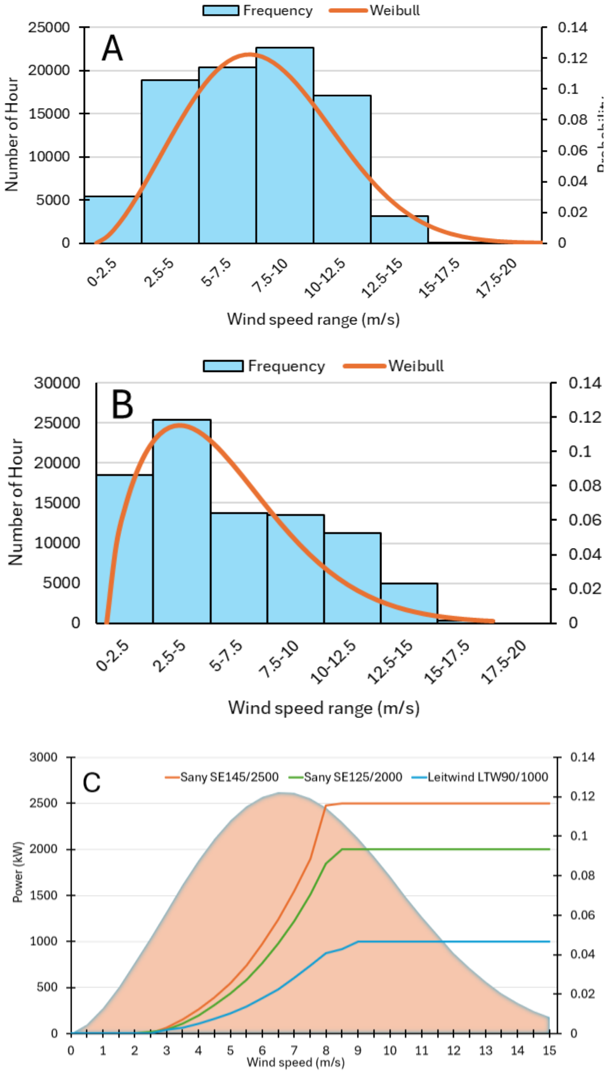

Fig 5. Ten-year Weibull PDF overlaid with the actual 10-year hourly wind speed frequency histogram for Ujungjaya (graph A); Ten-year Weibull PDF overlaid with the actual 10-year hourly wind speed frequency histogram for Panongan (graph B); and Power curves of all wind turbines overlaid with the wind speed distribution for Ujungjaya (graph C)

Ujungjaya (chart A), as previously stated, is rigidly locked into a strong southeastern flow, while Ujung Genteng (chart C) exhibits a bit more variation. While the dominant direction (approximately 40% of the time) is from the southeast, a significant secondary flow occurred from the east, with a faint trace from the west. Because the wind is spread over a larger arc, the highest frequency ring maxed out at 46.1%, whereas the highest frequency ring was 60% in the other charts. However, wind speeds remained high, with green (>10 m/s) dominating the southeast spoke.

Wates Kulon (chart D) differed from the other sites in terms of direction, which was most likely due to its different location, i.e., in East Java. The wind here was almost entirely southerly and extremely concentrated, blowing from the south approximately 60% of the time. The wind speeds were very strong at all locations, with the green and blue high-speed bands taking precedence. The charts show significant periods of wind speeds exceeding 7.5 m/s (blue and green sections) and consistent direction, thereby facilitating turbine placement. All three sites indicated strong regional and/or monsoonal influence.

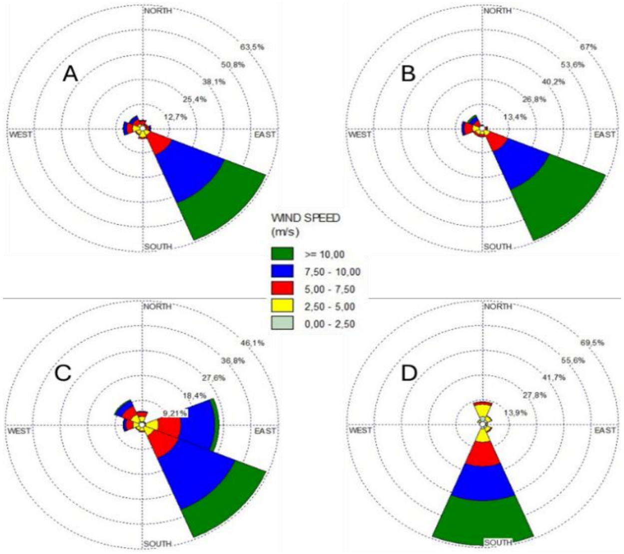

Fig 6. Wind roses for Ujungjaya in 2015 (chart A) and 2006 (chart B), Ujung Genteng in 2015 (chart C), and Wates Kulon in 2015 (chart D)

Table 5
Ten-year (2006–2015) average yearly energy generation of all wind turbines for all 11 locations

Loc No.	Locations	Wind Turbine	Energy (MWh)		10-year average yearly energy (MWh)
			Min	Max	
14	Wates Kulon, Lumajang	WT-1	3,690	5,451	4,903
		WT-2	7,462	10,979	9,889
		WT-3	9,419	13,798	12,446
16	Wongsorejo, Banyuwangi	WT-1	3,115	5,053	4,379
		WT-2	6,291	10,170	8,821
		WT-3	7,940	12,779	11,097
7	Cengal, Majalengka	WT-1	2,946	4,565	4,030
		WT-2	5,950	9,191	8,122
		WT-3	7,520	11,561	10,228
1	Ujungjaya, Pandeglang	WT-1	3,943	6,105	5,450
		WT-2	7,987	12,386	11,033
		WT-3	10,109	15,617	13,916
15	Sumberwaru, Situbondo	WT-1	2,958	4,852	4,266
		WT-2	5,979	9,777	8,610
		WT-3	7,577	12,310	10,859
2	Tamanjaya, Pandeglang	WT-1	3,441	5,542	4,929
		WT-2	6,976	11,206	9,989
		WT-3	8,848	14,122	12,614
5	Panongan, Cirebon	WT-1	2,662	4,399	3,889
		WT-2	5,374	8,865	7,842
		WT-3	6,812	11,161	9,887
17	Tiron, Kediri	WT-1	3,190	5,113	4,505
		WT-2	6,479	10,330	9,120
		WT-3	8,203	13,004	11,500
3	Ujung Genteng, Sukabumi	WT-1	3,741	5,724	5,167
		WT-2	7,607	11,602	10,489
		WT-3	9,659	14,631	13,250
13	Tugurejo, Ponorogo	WT-1	3,326	5,065	4,544
		WT-2	6,752	10,241	9,200
		WT-3	8,544	12,899	11,598
18	Sumber Klampok, Buleleng	WT-1	3,083	5,085	4,352
		WT-2	6,264	10,292	8,818
		WT-3	7,947	12,970	11,133

Table 5 shows the 10-year (2006–2015) average annual energy production along with the minimum and maximum values (MWh) for all 11 locations and the three different wind turbine capacities, as obtained from Equation 6. Variation of the power output from one location to another confirmed that the wind features, such as the Weibull parameters, influenced the amount

Table 6
Calculated capacity factors (CFs) for all wind turbines at all 11 locations

Loc No.	Location	CF (%)		
		WT-1	WT-2	WT-3
14	Wates Kulon, Lumajang	51.45	55.46	55.49
16	Wongsorejo, Banyuwangi	46.35	50.35	50.01
7	Cengal, Majalengka	43.56	47.50	46.50
1	Ujungjaya, Pandeglang	54.30	59.20	60.50
15	Sumberwaru, Situbondo	45.27	49.69	49.67
2	Tamanjaya, Pandeglang	48.80	53.80	54.90
5	Panongan, Cirebon	41.70	46.00	45.70
17	Tiron, Kediri	44.37	48.90	48.95
3	Ujung Genteng, Sukabumi	48.40	53.60	55.00
13	Tugurejo, Ponorogo	43.89	48.46	48.55
18	Sumber Klampok, Buleleng	42.62	47.26	47.37

of energy generated. Generally, the SE145/2500 turbine (WT-3) provided the most significant energy yield for almost all the sites because of its wide operating range and large rotor diameter.

Table 6 displays the CFs measured at each location, which is the level of turbine usage at each site. CF is a metric that measures how well the turbine capacity is utilised regardless of turbine size. The CF evaluation revealed that Ujungjaya is the best site for the SE145/2500 turbine based on a CF of 60.5%. This value indicates that the wind is likely to be within the turbine's operating range, making this site the first choice for turbine energy production. Other sites showed similar behaviour, with the CF trend pointing to increased turbine power and improved wind conditions.

The findings in Tables 5 and 6 provide three key insights for further investigation: the trade-offs between energy and CFs and energy and turbine capacity, and the broader implications for maximising energy efficiency. In terms of energy versus CF, Ujungjaya was clearly the most promising location because it presented the highest energy generation of 13,916 MWh and the highest CF of 60.5% when using WT-3. Wates Kulon also performed well, producing 12,446 MWh at a CF of 55.5%, making it nearly as promising as Ujungjaya. Similarly, Ujung Genteng delivered competitive results, producing 13,250 MWh with a CF of 55%. Tamanjaya was also an excellent location, producing 12,614 MWh and boasting a CF of 54.9%. Although Cengal, Panongan, Tugurejo, and Sumber Klampok performed well, they did not have the same potential, producing only approximately 10,000 MWh per year with WT-3 and exhibiting lower CF values of 45 to 47%. These locations would be inefficient and produce only a fraction of the energy of the top-tier sites.

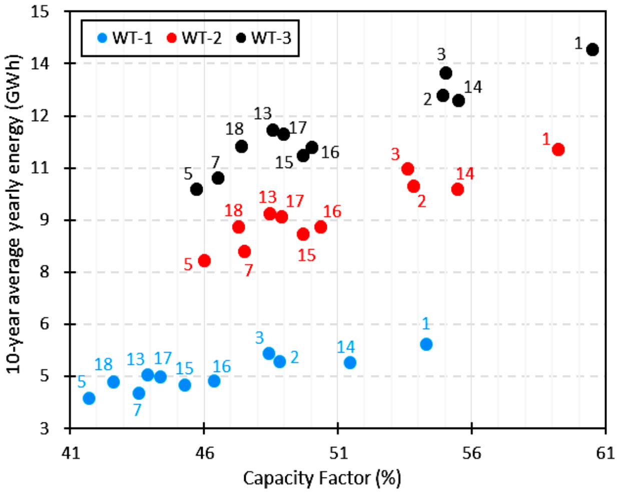

Fig 7. Plot of the trade-offs between the 10-year average yearly energy production and CF for all wind turbines (WT-1 to WT-3) across the 11 locations

Figure 7 depicts the trade-offs between energy generation and CF for all wind turbines at the 11 locations, which are identified by location number. For WT-3, the trade-off scatter plot shows clear distinctions between the sites. The top right quadrant, which indicates a good combination of high energy production and high CF, is dominated by Ujungjaya, Wates Kulon, Ujung Genteng, and Tamanjaya, indicating that they are the most promising sites for developing utility-scale wind farms. The middle cluster of the graph is primarily made up of the sites Wongsorejo, Tiron, and Sumberwaru, which have moderate CF values and reasonable annual energy yields, indicating potential for local or medium-scale projects. However, the bottom left quadrant includes the least suitable areas for large-scale deployment, with Cengal, Panongan, Tugurejo, and Sumber Klampok producing very little CF or energy. This distribution emphasises the importance of conducting local studies to determine the best turbine technology based on the local wind pattern.

The trade-off analysis of WT-1 and WT-2 revealed a consistent performance pattern across all turbine sizes. The four strongest sites that consistently appeared in the results were Ujungjaya, Wates Kulon, Ujung Genteng, and Tamanjaya, which produced abundant energy each year and exhibited good CF values. Wongsorejo, Tiron, and Sumberwaru were in the second tier and had moderate results, indicating good but not particularly competitive conditions. Cengal, Panongan, Tugurejo, and Sumber Klampok represented less desirable locations based on their low energy output and CF values. Increasing the size of the turbines significantly increases the total energy output; however, the relative ranking of the sites remained fairly constant. This means that location is the most important factor in determining performance, which rarely changes.

Ujungjaya, Wates Kulon, Ujung Genteng, and Tamanjaya exhibited high monthly generation and CF values; therefore, these sites are the most appropriate candidates for constructing turbines. Only a few sites exhibited the potential to generate a great deal of electricity, although they also showed lower efficiency. These sites included Wongsorejo (11,097 MWh, 50% CF), Tiron (11,500 MWh, ~49% CF), and Sumberwaru (10,859 MWh, ~49.7% CF). Thus, although they can generate a considerable amount of power, the efficiency of their turbines was low relative to that of the top-tier sites.

Installing larger turbines (WT-3) at Ujungjaya, Ujung Genteng, Wates Kulon, and Tamanjaya would result in the highest annual production. However, if the goal is to achieve the highest efficiency of the installed capacity, meaning that the

Table 7
Composite ranking of wind sites for WT-3 under three weighting schemes of energy generation and CF

Loc No.	Location	Ranking		
		Scheme 1: E50-CF50	Scheme 2: E70-CF30	Scheme 3: E30-CF70
1	Ujungjaya	1	1	1
3	Ujung Genteng	2	2	3
2	Tamanjaya	3	3	4
14	Wates Kulon	4	4	2
17	Tiron	5	5	6
15	Sumberwaru	6	6	7
16	Wongsorejo	7	7	5
13	Tugurejo	8	8	8
18	Sumber Klampok	9	9	9
7	Cengal	10	10	10
5	Panongan	11	11	11

turbines idle for fewer hours, then Ujungjaya, Wates Kulon, and Ujung Genteng once again represented the top choices because they not only consistently produce a high energy output but also have high CFs.

This paper does not provide a detailed modelling of the performance or energy output of existing wind farms in Indonesia. However, contextual comparisons with operational projects can better reveal whether the modelled wind resource and turbine performance in the Java–Bali region are realistic. For comparison purposes, this study discusses the operation of existing wind farms, i.e., Sidrap and Tolo in South Sulawesi. Sidrap wind farm area's annual average wind speed at 100 m height is approximately 5 to 7.5 m/s, and strong winds typically occur during the months from April to October (Lisapaly, 2021). Wind power plant Tolo operates based on wind speeds of 6 to 8 m/s (IESR, 2025). These wind regimes have allowed Indonesia to develop its first large-scale wind power plants. The average wind speeds over a long period are almost the same as those of the top-tier sites identified here (Ujungjaya and Wates Kulon). Thus, the simulated wind resource levels obtained for the Java–Bali region is not only in line with current operational conditions in Indonesia but also with the physically possible levels.

The operational CF for Sidrap is approximately 31.25% (Anditya, 2021). This value is similar to or even lower than the theoretical CFs revealed for the best sites in this study. However, it is worth noting that the CFs obtained from this study are merely theoretical values derived from wind speed distributions and turbine power curves. Obviously, in real environments, even lower CF values would be obtained due to wake effects, directional variability, and system losses. Still, this comparison provides a substantial empirical framework indicating that the projected wind energy potential in the Java–Bali region is not only theoretically attractive but also matches the current implementation of wind energy in Indonesia.

As mentioned in the methodology section, a quantitative rank displaying the order of locations with different energy and CF performances could be helpful for planners in considering the optimum wind farm siting. Table 7 displays the composite ranking of a weighted score combining energy and CF of locations for WT-3. It reveals the performance of locations with three different weighting schemes: (1) a balanced score of 50% energy and 50% CF, named as “Scheme 1: E50-CF50”; (2) 70% energy and 30% CF, named as “Scheme 2: E70-CF30”; and (3) 30% energy and 70% CF, named as “Scheme 3: E30-CF70”.

The composite ranking analysis confirmed that Ujungjaya (Pandeglang, Banten) is the most stable location because it consistently placed first across all weighting scenarios. Wates Kulon (Lumajang, East Java) exhibited strong sensitivity to CF prioritisation, rising to second place under the 30/70 weighting, whereas Ujung Genteng (Sukabumi, West Java) maintained a consistent position in the top three. Tamanjaya (Pandeglang, Banten) ranked high in energy-driven scenarios but fell slightly when CFs were considered, indicating that its advantage was based on the total yield rather than efficiency. The lower-tier sites, i.e., Cengal (West Java), Panongan (West Java), Tugurejo (East Java), and Sumber Klampok (Bali), remained at the bottom regardless of the weighting scheme, indicating their lack of competitiveness in both energy production and CFs.

The analysis results revealed that there are technical opportunities for deploying utility-scale wind turbines in low-wind areas near the equator, particularly in Indonesia's Java–Bali region. While the evaluation of different wind turbine capacities yielded sufficient CFs across all locations for various wind speed regimes, this study did not account for the logistical and transportation challenges encountered during turbine infrastructure construction. Moreover, this study did not focus on the best rotor configurations but rather selected standard turbines from the market to determine the level of potential energy production by the different turbine capacities.

While additional assessments of the economic aspects will significantly enhance investment decision-making and justify project feasibility, this study is purposefully positioned as a technical pre-feasibility and resource-based assessment rather than a comprehensive techno-economic evaluation. While metrics such as the levelised cost of electricity are critical for project-level investment decisions, they rely heavily on financial, regulatory, and market assumptions that are constantly changing in Indonesia. Therefore, this work established a technical foundation for future levelised cost of electricity-based and policy-oriented research. Moreover, future work should integrate more recent reanalysis and satellite-based products, such as ERA5, to update and extend the present assessment and evaluate potential climate-driven shifts in wind resources.

5. Conclusion

This study assessed the potential energy production and CFs of commercially available utility-scale wind turbines (1 MW, 2 MW, and 2.5 MW) in low-wind speed regions of the tropical Java–Bali region of Indonesia. It also analysed 10-year hourly time-based wind speed data from several locations based on the Weibull distribution, frequency, wind roses, and seasonal and diurnal patterns.

The wind class categorisation from the NREL was adopted to evaluate the wind energy potential at 11 locations across Banten, West Java, East Java, and Bali, Indonesia. A wind power density of 300 W/m is sufficient for operating large-scale wind turbines, with hub heights of approximately 100 m. The Weibull distribution parameters played a vital role in describing the wind power potential at these sites. An analysis of the trade-offs between energy generation and CFs showed that it would be possible to locate large-scale wind energy plants in areas with an average wind speed of 6.5 m/s or greater.

The top-tier sites had a high average wind speed and stable wind distribution, while the mid-tier sites had good wind speeds but less stable distributions. The study selected three HAWTs with varying capacities, namely the Leitwind LTW90/1000, Sany SE125/2000, and Sany SE145/2500, based on their suitability with the sites' wind power density. This study also presented the calculation results for the 10-year average yearly energy production and CFs of all locations. This finding revealed that Ujungjaya, a location in Pandeglang, Banten, is the most promising for deploying utility-scale wind turbines in low-wind areas near the equator. The study also found that Ujungjaya, Wates Kulon, Ujung Genteng, and Tamanjaya had high annual generation and high CFs, which makes them the best sites to develop.

Although large-rotor, low-specific-power turbines exhibit superior performance in low-wind sites, the paper provides empirical evidence for promoting wind power in equatorial Southeast Asia from a measured wind data perspective. The findings revealed that the turbine energy yield and CFs are very sensitive to rotor diameter at low-wind speeds. Moreover, the ranking of turbines varied significantly between sites with similar annual mean wind speeds. This underscores the necessity of performing site-specific turbine selection and not applying average global turbine class standards, which appears to be customary at many tropical sites.

The results of this study also demonstrate that in low-wind regions (including tropical low-wind), utility-scale projects can be successfully implemented by performing careful siting, utilising long-term wind speed data, and deploying modern large-rotor/large blade swept areas and low-specific-power turbines specific for low-wind sites. This further emphasises the significance of customised energy transition plans for developing nations. By showing that some locations in the Java–Bali system meet reasonable annual energy outputs and exhibit high CF values, this study offers practical policy recommendations for Indonesia and other low-wind regions.

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