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Performance Evaluation of a Diffuser-Augmented Horizontal Axis Wind Turbine for Energy Generation in Low-Wind Environments

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ABSTRACT

This study evaluated the performance of a diffuser-augmented horizontal axis wind turbine (DAHAWT) for energy generation in low-wind environments. By integrating a flanged diffuser around a conventional horizontal axis wind turbine (HAWT), the investigation examined whether diffuser augmentation could enhance startup characteristics, electrical generation, and operational performance under naturally occurring wind conditions. A descriptive-experimental and comparative research design was employed through the fabrication and field testing of HAWT and DAHAWT systems in Santo Tomas, Pangasinan, Philippines. Wind speed, rotor rotational speed, voltage output, current output, power output, power coefficient, and battery-charging performance were measured and analyzed. The results showed that the DAHAWT achieved a lower cut-in wind speed of approximately 1.62–1.70 m/s compared with 2.5–3.0 m/s for the conventional HAWT, representing a reduction of about 35–40%. The diffuser-augmented configuration also achieved higher maximum rotational speed (973 RPM vs. 682 RPM) and voltage output (19.7 V vs. 13.82 V), corresponding to improvements of approximately 43% in both parameters. Mean current output increased by approximately 102%, while average electrical power output improved by approximately 186%. In addition, the DAHAWT achieved a 28.4% higher mean reference-area-based power coefficient and operated in battery-charging mode seven times more frequently than the conventional HAWT. These findings indicate that diffuser augmentation improved aerodynamic energy capture and electrical performance under the tested conditions, highlighting the potential of DAHAWT systems for small-scale wind-energy generation in low-wind environments.

Keywords: Diffuser-Augmented Wind Turbine, Horizontal Axis Wind Turbine, Wind Energy Generation, Low-Wind Environments, Renewable Energy Systems

INTRODUCTION

The increasing demand for clean, reliable, and sustainable energy has accelerated the global transition toward renewable energy technologies capable of reducing dependence on fossil fuels and mitigating the environmental impacts of climate change. Among the available renewable energy resources, wind energy continues to attract significant attention because of its abundance, scalability, low operational emissions, and applicability to both utility-scale and decentralized power-generation systems (International Energy Agency, 2023; Burton et al., 2011; Manwell et al., 2010). However, conventional Horizontal Axis Wind Turbines (HAWTs) face operational bottlenecks in regions characterized by low wind speeds. Small-scale HAWTs typically require relatively high and consistent threshold velocities to reach cut-in conditions and generate usable electricity (Bianchini et al., 2022; Mathew, 2006). Consequently, their aerodynamic efficiency sharply declines in rural and semi-urban areas where localized wind resources are weak, intermittent, and highly variable (Chen & Fang, 2015). This geographic limitation is particularly pronounced in the inland regions of the Philippines, where average wind velocities frequently fall below the optimal operating thresholds of standard small-scale turbines (Olalo et al., 2022).

Wind energy development in the Philippines has primarily focused on large-scale and offshore applications. For instance, research by Maañdal et al. (2021) demonstrated the technical and economic viability of offshore wind-energy projects in selected Philippine locations. While such studies underscore the growing role of wind energy in the country's renewable-energy portfolio (Twidell & Weir, 2021), they also highlight the need for alternative technologies that can effectively harness lower wind resources available in inland communities. Improving turbine performance under these conditions remains an important engineering challenge (Veers et al., 2023).

A promising solution is the Diffuser-Augmented Wind Turbine (DAWT), which integrates a diffuser or shroud around the rotor to accelerate airflow and increase the mass flow rate passing through the turbine. By creating a favorable pressure differential across the rotor plane, the diffuser enhances local wind velocity and improves aerodynamic energy extraction, resulting in higher rotational speeds, increased electrical generation, and improved overall turbine performance (Ohya & Karasudani, 2010; Naji & Jabbar, 2024; Hansen, 2015). Previous investigations have consistently reported that diffuser augmentation can improve airflow concentration, reduce cut-in wind speed, and increase energy capture in low-wind environments. Computational and experimental studies have demonstrated significant performance gains through the use of optimized diffuser geometries, flanged diffuser configurations, inlet shrouds, and high-lift aerodynamic profiles (Kannan et al., 2013; Hu & Wang, 2015; Irawan & Harianto, 2019; Chhetri et al., 2021; Paranjape et al., 2021). Furthermore, review studies conducted by Al-Quraishi et al. (2019) and Agha (2019) emphasized the strong potential of DAWT systems for small-scale electricity generation in urban, rural, and low-wind settings.

However, while the aerodynamic benefits of diffuser augmentation have been widely documented through computational fluid dynamics simulations, laboratory experiments, and analytical modeling, comparatively fewer studies have evaluated the real-world performance of DAWT systems under actual operating conditions in the Philippines. Existing literature also provides limited field-based evidence regarding practical energy-generation outcomes, particularly with respect to startup behavior, electrical generation, and battery-charging capability under naturally occurring low-speed wind conditions (Castro et al., 2024).

To address these research gaps, this study evaluated the performance of a Diffuser-Augmented Horizontal Axis Wind Turbine (DAHAWT) for energy generation in the low-wind environment of Poblacion West, Santo Tomas, Pangasinan, Philippines. Specifically, the study sought to: (1) determine and compare the cut-in wind speed of the DAHAWT and a conventional HAWT; (2) evaluate and compare the rotor rotational speed (RPM), voltage output, and battery charging characteristics of both turbine configurations; and (3) determine whether significant differences exist in the operational performance of the two systems under similar environmental conditions.

The study contributes field-based experimental evidence on the aerodynamic and electrical performance of a fabricated DAHAWT operating under naturally occurring low-wind conditions in the Philippines. By linking aerodynamic enhancement mechanisms with practical energy-generation outcomes, including voltage production and battery-charging capability, the findings provide localized validation of diffuser-augmentation technology and contribute to the growing body of knowledge on low-speed wind-energy harvesting systems.

METHODS

This study employed a descriptive-experimental and comparative quantitative research to evaluate and compare the aerodynamic and electrical performance of a Diffuser-Augmented Horizontal Axis Wind Turbine (DAHAWT) relative to a conventional Horizontal Axis Wind Turbine operating under identical low-wind conditions. Experimental research is suited for examining the effects of a controlled intervention on measurable outcomes, while comparative analysis facilitates the systematic evaluation of performance differences between systems subjected to similar operating conditions (Creswell Creswell, 2018).

In this study, the diffuser served as the primary experimental intervention, and turbine performance was evaluated by comparing cut-in wind speed, rotor rotational speed (RPM), voltage output, current output, power output, power coefficient, and battery-charging performance. This research design enabled a systematic comparison of the two turbine configurations under naturally occurring environmental conditions.

Study Area

Field testing was conducted in Poblacion West, Santo Tomas, Pangasinan, Philippines. The location was selected because it exhibits low- to moderate-wind characteristics representative of many rural and semi-urban communities throughout the country. Prior to experimentation, preliminary wind profiling was performed to confirm the suitability of the site for evaluating small-scale wind turbine performance under low-wind environmental conditions.

Turbine Configuration and Diffuser Design

Two turbine configurations were fabricated and evaluated: a conventional HAWT and a DAHAWT. Both systems employed the same three-bladed horizontal-axis rotor with a rotor diameter of 107.6 cm and a NACA 4412 airfoil profile. The rotor was directly coupled to a 24 V, 300 W permanent magnet generator through a direct-drive arrangement. Maintaining identical rotor and generator assemblies ensured that any observed differences in performance could be attributed primarily to the diffuser augmentation (Khalid et al., 2020).

The DAHAWT incorporated a flanged diffuser fabricated from steel plate material. The diffuser measured 45.72 cm in length and featured an inlet diameter of 139.7 cm and an outlet diameter of 152.4 cm, producing an expansion ratio of approximately 1.19 and a diffuser angle of 15.5°. A circumferential flange with a height of 30.48 cm was installed at the diffuser outlet. The rotor was positioned concentrically within the diffuser, maintaining an approximate radial clearance of 16.1 cm between the blade tips and the diffuser wall. The overall arrangement of the turbine, generator, charge controller, and battery system is illustrated in Figure 1.

The diffuser geometry was selected based on diffuser-augmentation principles reported by Ohya and Karasudani (2010), Hu and Wang (2015), and Paranjape et al. (2021). The diffuser inlet area was approximately 1.533 m^2, while the rotor swept area was approximately 0.909 m^2, resulting in an inlet-to-rotor area ratio of about 1.69. The selected diffuser angle was intended to encourage airflow expansion while minimizing excessive flow separation. Meanwhile, the outlet flange was incorporated to promote vortex formation and strengthen the low-pressure region downstream of the turbine. Together, these aerodynamic mechanisms increase the mass flow rate passing through the rotor and enhance performance under low-speed wind conditions. The principal dimensions and geometric characteristics of the diffuser are presented in Figure 2, while the complete technical specifications of the DAHAWT system are summarized in Table 1.

The electrical subsystem consisted of a permanent magnet generator, charge controller, and a 12 V, 400 Ah sealed lead-acid battery used for energy storage. Electrical output was continuously monitored throughout the testing period to evaluate charging behavior and overall system performance.

Figure 1

Schematic Diagram of the Diffuser-Augmented Horizontal Axis Wind Turbine

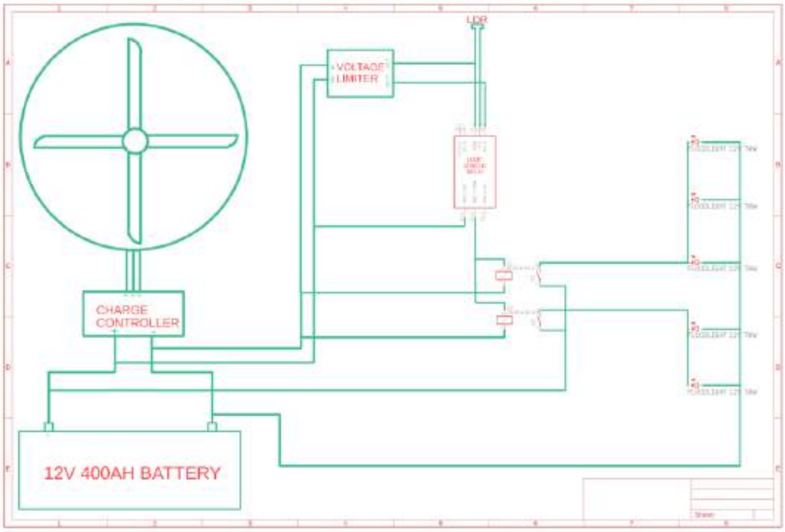


Figure 2

Dimensions of the Diffuser-Augmented Horizontal Axis Wind Turbine

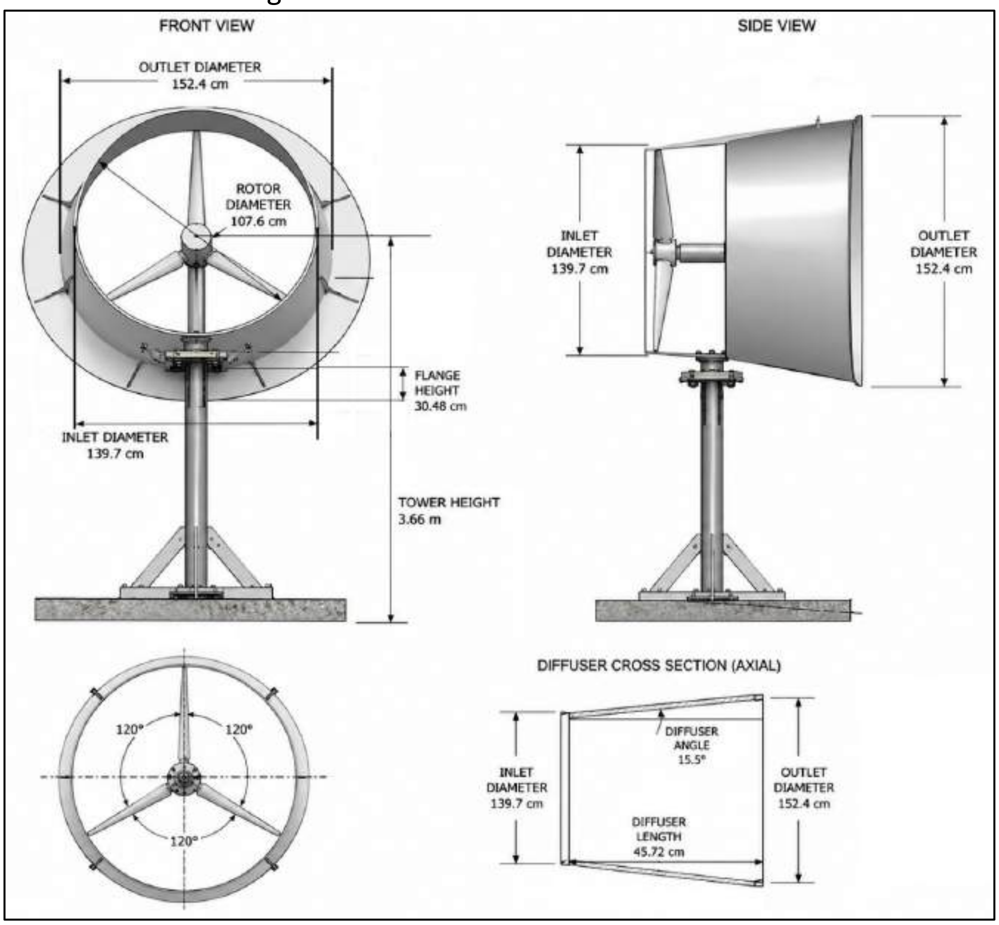


Table 1
Technical Specifications of the DAHAWT System

Parameter	Specification
Turbine Type	Horizontal Axis Wind Turbine
Number of Blades	3
Rotor Diameter	107.6 cm
Blade Material	Nylon Fiber
Blade Length	53.8 cm
Blade Profile	NACA 4412 Airfoil
Generator Type	Permanent Magnet Generator
Generator Rating	24 V, 300 W
Tower Height	3.66 m
Battery Type	Sealed Lead-Acid Battery
Battery Rating	12 V, 400 Ah
Charge Controller Type	PWM / MPPT
Diffuser Material	Steel Plate
Diffuser Length	45.72 cm
Inlet Diameter	139.7 cm
Outlet Diameter	152.4 cm
Diffuser Expansion Ratio	1.19
Diffuser Angle	15.5°
Flange Height	30.48 cm

Data Collection and Experimental Procedure
Field testing was conducted over four consecutive days. Both turbine configurations were installed at a height of 3.66 m above ground level and exposed to the same environmental conditions. Throughout the testing period, the systems were oriented toward the prevailing wind direction to ensure comparable wind exposure.

Measurements were recorded at 10-minute intervals using calibrated instruments. Wind speed was measured with a digital anemometer, rotor rotational speed with a digital tachometer, voltage output with a digital voltmeter, and current output with an ammeter integrated into the charging circuit. Battery charging status was monitored through charge-controller indicators and battery voltage observations.

The parameters evaluated included wind speed (m/s), rotor rotational speed (RPM), voltage output (V), current output (A), power output (W), power coefficient, battery charging status, and cut-in wind speed. Cut-in wind speed was defined as the minimum wind velocity at which measurable electrical generation first occurred.

To improve testing consistency, both turbine configurations utilized identical rotor assemblies, generator ratings, electrical loading arrangements, measurement instruments, and installation heights. Measurements were obtained using a paired-observation approach to minimize the influence of natural wind variability between turbine configurations. All instruments were calibrated and operated in accordance with manufacturer specifications. The actual field-testing arrangement used during data collection is shown in Figure 3.

Figure 3
Diffuser-Augmented Horizontal Axis Wind Turbine Test Setup

Performance Calculations
The electrical power output was calculated using:

$$\mathbf{P_{out} = VI} \qquad \text{(Eq. 1)}$$

where $\mathbf{P_{out}}$ is the electrical power output (W), **V** is the measured voltage (V), and **I** is the measured current (A).

Available wind power was estimated using:

$$\mathbf{P_{wind} = \tfrac{1}{2}\rho A V^3} \qquad \text{(Eq. 2)}$$

where $\mathbf{P_{wind}}$ is the reference wind power (W), **ρ** is the air density (1.225 kg/m³), **A** is the selected reference area (m²), and **V** is the measured free-stream wind speed (m/s). For the conventional HAWT, **A** was taken as the rotor swept area. For the DAHAWT, **A** was calculated using the diffuser inlet diameter to account for the larger geometric capture area introduced by the shroud.

The power coefficient was calculated as:

$$\mathbf{C_p = P_{out} / P_{wind}} \qquad \text{(Eq. 3)}$$

In this study, $\mathbf{C_p}$ was used as a reference-area-normalized performance indicator rather than as a direct measure of true aerodynamic efficiency. This distinction is important for diffuser-augmented turbines because the diffuser modifies the upstream and downstream pressure field, accelerates the local airflow through the rotor, and increases the effective mass flow rate. Consequently, $\mathbf{C_p}$ values obtained for diffuser-augmented systems depend strongly on the selected reference area and should not be interpreted in the same manner as the Betz-limited coefficient of an unshrouded rotor. Similar treatment of performance coefficients in diffuser-augmented and wind-lens turbine studies has been reported by Ohya and Karasudani (2010), Hansen et al. (2000), and Al-Quraishi et al. (2019).

Battery Charging Performance Interpretation

Battery charging performance was evaluated primarily through direct field observations of charging occurrence, charging duration, charge-controller status, measured voltage output, and measured current output during the testing period. These experimentally observed results were used to compare the practical charging behavior of the HAWT and DAHAWT configurations under the same low-wind field conditions.

Manufacturer-provided charging characteristic curves for the 12 V, 400 Ah sealed lead-acid battery were used only as an engineering reference to support interpretation of the observed charging behavior. These curves describe typical charging-voltage, charging-current, and state-of-charge trends for the battery type used in the study; however, they were not generated from the field experiment. Accordingly, any discussion of state-of-charge progression, bulk charging, absorption charging, or current tapering was treated as interpretive context rather than direct experimental evidence.

Statistical Analysis

The researchers organized and analyzed the collected data using quantitative statistical techniques. Descriptive statistics, including means, standard deviations, minimum values, maximum values, and graphical trend analyses, were used to summarize turbine performance characteristics.

Paired-sample t-tests were conducted to determine whether significant differences existed between the DAHAWT and HAWT with respect to RPM and voltage output under comparable wind conditions. This statistical method is appropriate for comparing two related groups measured under similar experimental conditions (Field, 2018).

Simple linear regression and curve-fitting analyses were used to describe the observed relationships between wind speed and selected turbine performance variables, including RPM, voltage output, current output, and power output. Regression analysis is widely used in engineering research to quantify relationships among continuous variables and assess predictive performance (Montgomery et al., 2021). The resulting equations, correlation values, and coefficients of determination were interpreted as indicators of association and model fit within the collected field dataset. They were not treated as independent proof of engineering superiority. Engineering interpretation was based on the combined evidence from measured performance differences, descriptive statistics, charging observations, aerodynamic behavior, and the known operating principles of diffuser-augmented turbines. Because the measurements were obtained from a single field setup over a limited observation period, the regression findings should be understood as site- and period-specific descriptions of turbine behavior.

The chi-square test of independence was employed to examine the association between turbine configuration and battery charging status. Effect size was evaluated using Cramer's V. This statistical procedure is appropriate for assessing relationships between categorical variables (McHugh, 2013).

All statistical analyses were conducted using a significance level of $\alpha = 0.05$, and were interpreted with consideration of the assumptions and constraints of the field-testing design. The paired-sample t-tests assume that paired differences are approximately normally distributed, while the regression analyses assume an approximately linear relationship, constant error variance, and independent residuals. The chi-square test assumes independent categorical observations and adequate expected cell counts. Although the paired observation approach helped reduce the effect of natural wind variability, the measurements were collected repeatedly from the same experimental setup over a limited four-day observation period. Therefore, adjacent measurements may not be fully independent because of short-term wind persistence, site-specific turbulence, and repeated use of the same turbine assemblies and electrical loading conditions.

For this reason, statistical significance was interpreted as evidence of performance differences within the observed field-test conditions rather than as a definitive basis for broad generalization. The p-values were considered together with descriptive statistics, effect size, engineering magnitude, and the physical behavior of the turbine systems.

Safety and Site Management Procedures

Before testing commenced, all turbine systems underwent mechanical and electrical inspection to ensure safe operation. Rotor assemblies, support structures, electrical wiring, and battery connections were inspected before each testing session. A safety clearance zone was maintained around the turbine installations, and testing was suspended whenever adverse weather conditions were encountered. The experimental site was selected to minimize interference with public activities while providing adequate wind exposure for performance evaluation. Prior to installation, coordination was undertaken with local stakeholders to facilitate safe field operations. Electrical connections were properly insulated and continuously monitored during testing. The turbine systems operated exclusively through wind energy and did not involve fuel consumption, hazardous emissions, or environmentally harmful materials.

Limitations

This study focused on the comparative evaluation of the aerodynamic and electrical performance of a Diffuser-Augmented Horizontal Axis Wind Turbine (DAHAWT) and a conventional Horizontal Axis Wind Turbine (HAWT) under naturally occurring low-wind conditions. Accordingly, the investigation did not include a detailed techno-economic assessment, life-cycle cost analysis, long-term structural durability evaluation, or long-term energy-yield analysis. These aspects remain important considerations for future studies evaluating the practical implementation of diffuser-augmented wind turbine systems.

Battery-charging performance was assessed primarily through observed charging occurrence, charging duration, measured voltage output, and measured current output during field testing. Continuous monitoring of cumulative ampere-hour delivery, battery state-of-charge progression, and long-term energy-storage performance was beyond the scope of the present investigation. Consequently, discussions based on manufacturer-provided charging characteristics are intended only to provide engineering context and should not be interpreted as direct experimental measurements.

Furthermore, the findings were derived from a single field-testing location over a four-day observation period. Although the paired-observation approach minimized the influence of short-term wind variability, the results should be interpreted within the environmental conditions under which the experiment was conducted. Additional studies involving longer monitoring periods, multiple testing locations, and varying wind regimes would further strengthen the generalizability of the findings.

RESULTS

This section presents the findings obtained from the comparative evaluation of the Diffuser-Augmented Horizontal Axis Wind Turbine (DAHAWT) and the conventional Horizontal Axis Wind Turbine (HAWT) under actual low-wind environmental conditions. The results are organized according to the principal performance indicators investigated, including wind profile characteristics, cut-in wind speed, rotor rotational speed (RPM), voltage generation, current output, power output, power coefficient, and battery charging performance.

Wind Profile Characteristics

Preliminary wind profiling conducted in Poblacion West, Santo Tomas, Pangasinan confirmed that the study site experiences low- to moderate-wind conditions appropriate for evaluating small-scale wind-energy systems intended for low-wind applications. Throughout the testing period, wind velocities exhibited sufficient variation to assess both startup behavior and operational performance under naturally fluctuating environmental conditions.

The recorded wind profile further indicated that naturally occurring wind speeds frequently approached the operational threshold of conventional small-scale HAWTs. As a result, the site provided a suitable environment for assessing the effectiveness of diffuser augmentation in enhancing wind-energy harvesting under low-speed wind conditions.

Cut-In Wind Speed Performance

Experimental observations showed that the DAHAWT initiated electrical generation at substantially lower wind speeds than the conventional HAWT. Measurable voltage output was consistently observed in the DAHAWT at approximately 1.62–1.70 m/s, whereas the HAWT generally required wind speeds of approximately 2.5–3.0 m/s before electrical generation occurred.

This reduction in cut-in wind speed corresponds to an improvement of approximately 35–40%, enabling the DAHAWT to remain operational during periods when the conventional HAWT was unable to generate electricity. Earlier startup effectively extends potential operating time and increases opportunities for energy capture in low-wind environments.

The observed reduction in cut-in wind speed aligns with previous diffuser-augmentation studies that reported enhanced startup characteristics and improved airflow concentration in diffuser-assisted wind turbine systems (Ohya & Karasudani, 2010; Hu & Wang, 2015; Chhetri et al., 2021).

Aerodynamic Basis of DAHAWT Performance Enhancement

The improved startup behavior of the DAHAWT can be attributed to the aerodynamic influence of the diffuser surrounding the rotor. By creating a low-pressure region downstream of the turbine, the diffuser increases the effective mass flow rate passing through the rotor plane. This pressure differential accelerates airflow within the diffuser throat, producing local wind velocities at the rotor that exceed the free-stream wind velocity (Hansen et al., 2000; Manwell et al., 2010).

The flanged diffuser configuration further strengthens this effect through the formation of vortical structures near the diffuser outlet. These vortices intensify the downstream low-pressure wake and draw additional airflow through the turbine (Ohya et al., 2012). Consequently, the DAHAWT is capable of initiating operation at lower wind speeds and capturing more energy under low-speed wind conditions.

These observations are consistent with wind-lens theory and prior diffuser-augmentation studies reporting improved airflow concentration and energy extraction (Ohya & Karasudani, 2010; Al-Quraishi et al., 2019; Naji & Jabbar, 2024). The same aerodynamic mechanisms that reduced cut-in wind speed likely contributed to the higher rotational speed, electrical output, and charging occurrence observed in the DAHAWT.

Rotor Rotational Speed (RPM)

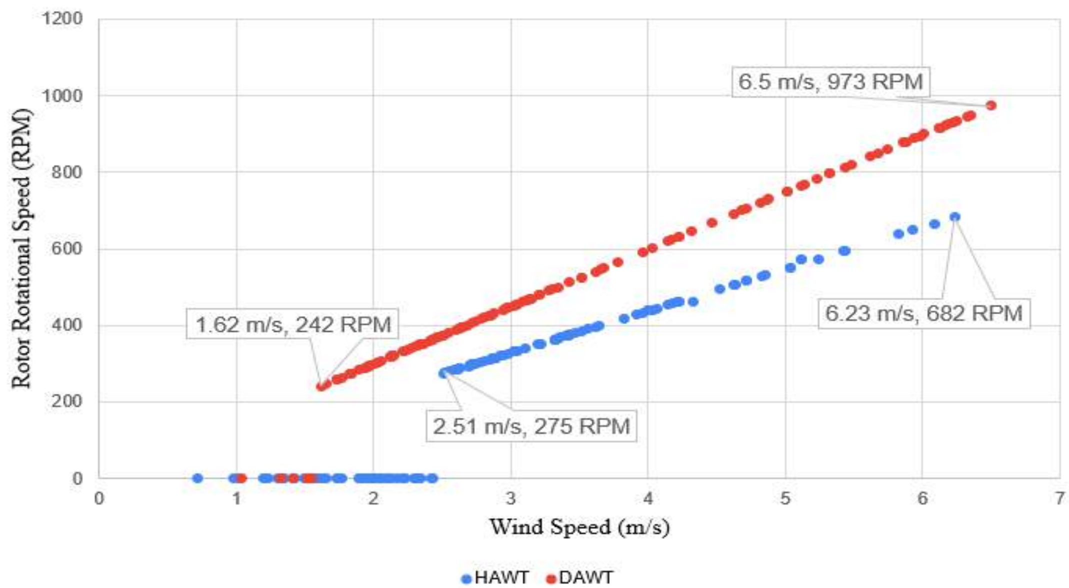
The DAHAWT consistently achieved higher rotational speeds than the conventional HAWT under comparable wind conditions. As shown in Figure 4, the DAHAWT attained a maximum recorded rotational speed of 973 RPM, whereas the HAWT reached a maximum of 682 RPM. These results indicate a substantial enhancement in rotor performance under low-wind operating conditions.

Statistical comparison supported the observed performance advantage of the diffuser-augmented configuration under the tested field conditions. As summarized in Table 2, the DAHAWT achieved a mean rotational speed of 486.37 RPM, compared with 252.41 RPM for the

HAWT, representing an increase of approximately 93%. Paired-sample t-test analysis showed that this difference was statistically significant, $t(143) = -16.58$, $p < 0.001$.

Figure 4

Comparison of HAWT and DAHAWT in terms of Wind Speed and RPM



Note. The best-fit linear models describing these relationships are given by:
HAWT_RPM = 158 (*HAWT_WS*) – 206 and *DAHAWT_RPM* = 157 (*DAHAWT_WS*) − 32.83

Table 2

Test of difference in RPM between HAWT and DAHAWT

Comparison	Mean	Std. Dev.	t	df	p-value
HAWT_RPM	252.41	202.18	-16.58	143	<0.001
DAHAWT_RPM	486.37	231.19			

Note. RPM was measured using a tachometer under AC generator, single-phase conditions.

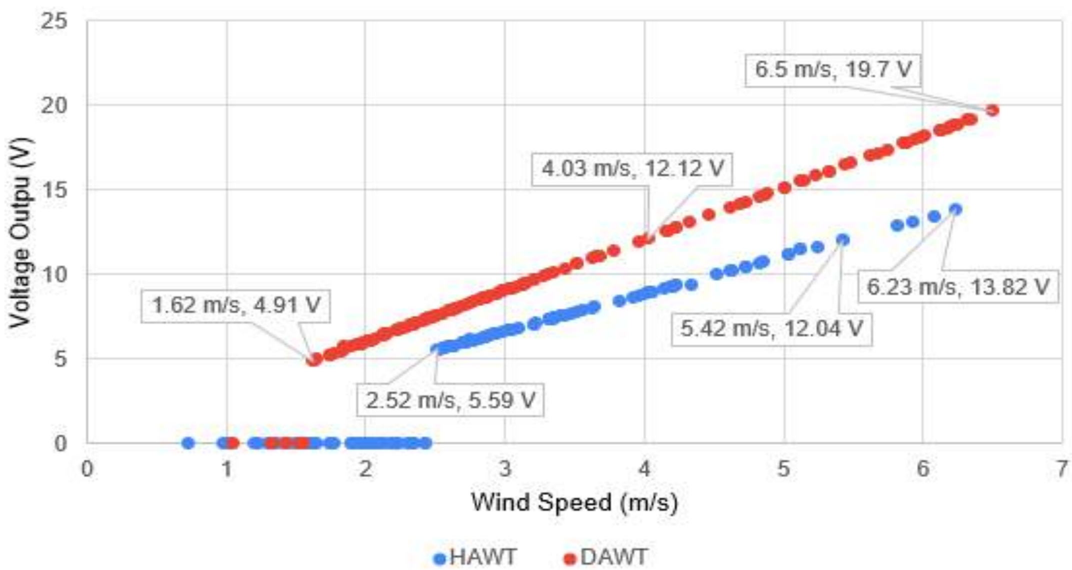
Regression analysis showed a strong positive relationship between wind speed and rotational speed ($R = 0.906$, $R^2 = 0.820$), indicating that RPM increased with wind speed within the observed dataset. The higher measured RPM of the DAHAWT is interpreted primarily in conjunction with the paired comparison results and the expected aerodynamic effect of the diffuser.

Voltage Output Performance

Voltage measurements likewise demonstrated superior electrical generation performance for the DAHAWT. As illustrated in Figure 5, the diffuser-augmented turbine generated measurable voltage at lower wind speeds and achieved a maximum observed voltage output of approximately 19.7 V. In contrast, the conventional HAWT reached a maximum voltage output of approximately 13.82 V.

Figure 5

Comparison of HAWT and DAHAWT in terms of Wind Speed and Voltage



Note. The best-fit linear models describing these relationships are given by:
HAWT_V = 3.21 (*HAWT_WS*) − 4.17 and *DAHAWT_V* = 3.18 (DA*HAWT_WS*) + 0.68

The statistical comparison presented in Table 3 shows that the DAHAWT produced a mean voltage output of 9.79 V, compared with 5.11 V for the HAWT. Paired-sample t-test analysis indicated that this difference was statistically significant, $t(143) = -16.17$, $p < 0.001$.

Table 3

Test of difference of the Output Voltage, in Volts (V), between HAWT and DAHAWT

Comparison	Mean	Std. Dev.	t	df	p-value
HAWT_V	5.11	4.10	-16.17	143	<0.001
DAHAWT_V	9.79	1.67			

Note. Voltage was measured under AC generator, single-phase conditions.

Regression analysis showed a strong association between wind speed and voltage output within the measured range ($R^2 \approx 0.82$). However, the practical advantage of the DAHAWT is supported primarily by its lower startup wind speed, higher measured voltage output, and more frequent charging operation under comparable field conditions.

Battery Charging Performance

Battery charging observations further highlighted the operational advantage of the DAHAWT under low-wind conditions. As summarized in Table 4, the DAHAWT achieved charging operation during 42 observation intervals (29.2%), whereas the HAWT entered charging mode during only 6 intervals (4.2%). These values were obtained directly from field observations based on charge-controller status, battery-voltage response, and measured electrical output during the testing period.

Table 4

Crosstabulation of Wind Turbine Type and Battery Status

Type	C (n, %)	NC (n, %)	Total (n, %)
HAWT	6 (4.2%)	138 (95.8%)	144 (100%)
DAHAWT	42 (29.2%)	102 (70.8%)	144 (100%)
Total:	48 (16.7%)	240 (83.3%)	288 (100%)

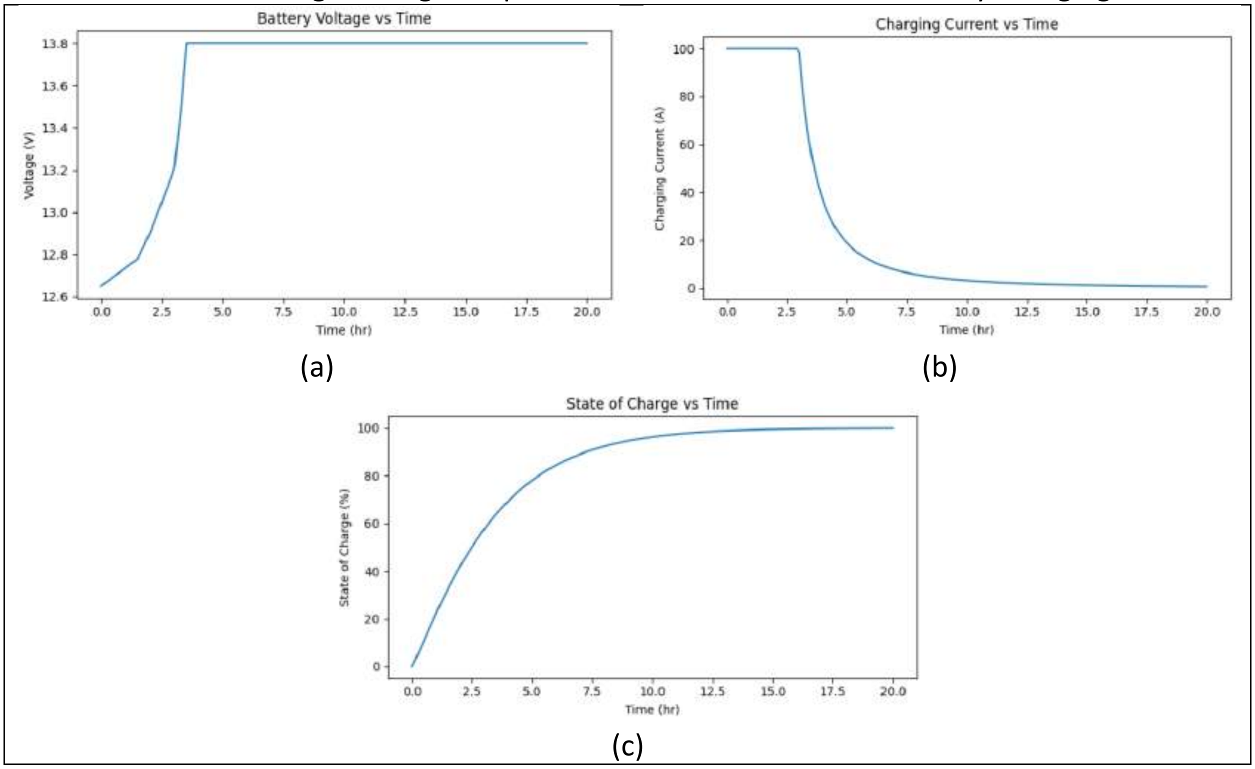
Note. C = Charging; NC = Not Charging. All expected cell counts are greater than 5. The association between type and battery status was statistically significant at $p < 0.001$.

Chi-square analysis revealed a statistically significant association between turbine configuration and battery charging status, $\chi^2(1) = 32.40$, $p < 0.001$. The computed Cramer's V value of 0.335 indicates a moderate association between turbine type and charging effectiveness. These experimentally observed results show that the diffuser-augmented turbine entered charging mode more frequently than the conventional HAWT under comparable low-wind conditions (Katooli & Noorollahi, 2022). Such behavior suggests improved suitability for battery-supported renewable-energy applications (Dogru & Yilmaz, 2024).

Estimated Battery Charging Characteristics

To provide additional engineering context, the charging behavior of the 12 V, 400 Ah sealed lead-acid battery was also interpreted using manufacturer-provided charging characteristics. As shown in Figure 6, these reference curves illustrate typical charging-voltage, charging-current, and state-of-charge trends for sealed lead-acid batteries. They are included only to explain the expected battery response once charging occurs and should not be interpreted as direct measurements obtained during the field test.

Figure 6
Manufacturer-Based Engineering Interpretation of Sealed Lead-Acid Battery Charging Behavior



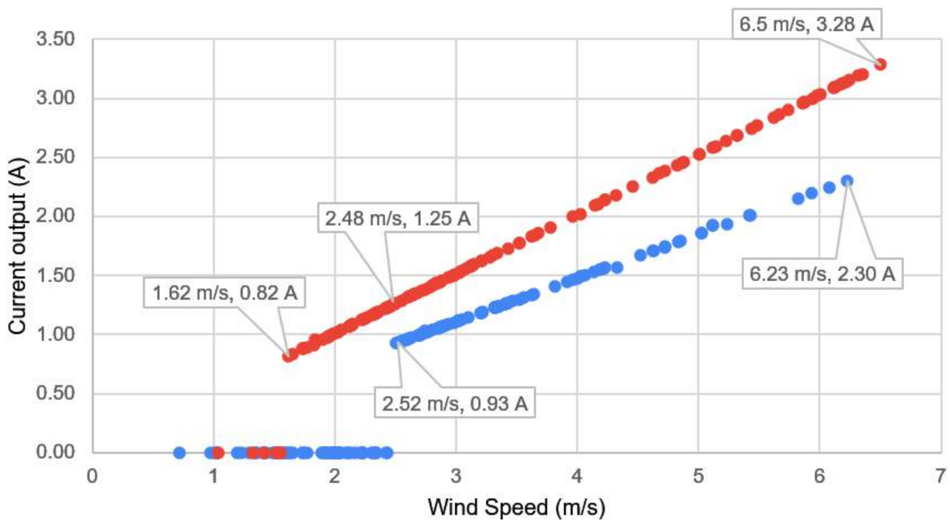
Note. The charging-voltage, charging-current, and state-of-charge curves shown in this figure are based on manufacturer-provided charging characteristics for the battery type used in the study. They are provided as interpretive engineering references only and were not directly measured during the field-testing period.

Although charging occurrence, charging duration, voltage output, and current output were monitored experimentally, cumulative ampere-hour delivery and continuous state-of-charge progression were not directly measured. Accordingly, the battery charging curves in Figure 6 are included only as manufacturer-based engineering references and not as direct experimental evidence.

Current Output Performance

Measured current outputs revealed a substantial improvement in charging capability for the DAHAWT. As shown in Figure 7, the diffuser-augmented configuration consistently produced higher output currents across the entire range of measured wind speeds, indicating more effective utilization of the available wind resource.

Figure 7
Comparison of HAWT and DAHAWT in terms of Wind Speed and Current



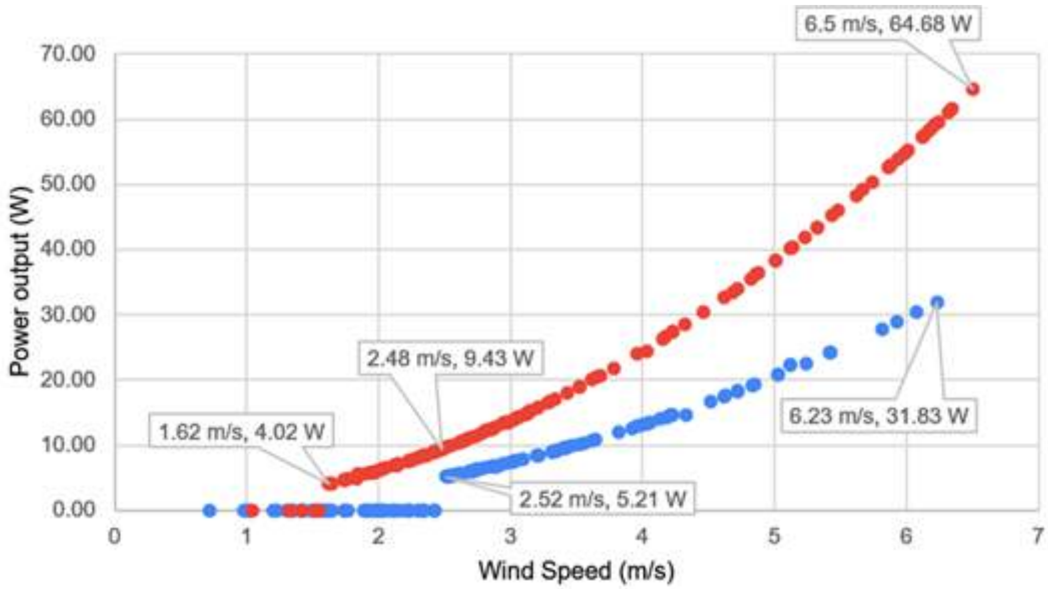
Note. The best-fit linear models describing these relationships are given by:
HAWT_C = 0.554 (*HAWT_WS*) − 0.790 (with R^2 = 0.8696)
and *DAHAWT_C* = 0.532 (*DAHAWT_WS*) − 0.118 (with R^2 = 0.9692)

The DAHAWT achieved a mean output current of approximately 1.645 A, whereas the HAWT produced a mean current of approximately 0.813 A, representing an increase of about 102%. The smaller negative intercept in the DAHAWT regression model is consistent with the earlier onset of useful charging current at lower wind speeds, supporting the previously observed reduction in cut-in wind speed. The higher R^2 value for the DAHAWT should be interpreted only as indicating a closer fit between wind speed and current output within the collected dataset, not as independent proof of engineering superiority (Lipian et al., 2019).

Power Output Performance

Electrical power output was calculated using Eq. (1), where power is obtained from the product of measured voltage and current. The resulting calculations revealed a substantial increase in energy-generation capability attributable to diffuser augmentation. As illustrated in Figure 8, the DAHAWT consistently generated higher electrical power than the conventional HAWT across comparable wind conditions.

Figure 8
Comparison of HAWT and DAHAWT in terms of Wind Speed and Power



Note. The best-fit curve models describing these relationships are given by: $HAWT\_P = -0.189\,(HAWT\_WS)^3 + 2.63\,(HAWT\_WS)^2 - 4.31\,(HAWT\_WS) + 0.851$ (with $R^2 = 0.9764$) and $DAHAWT\_P = 0.098\,(DAHAWT\_WS)^3 + 0.284\,(DAHAWT\_WS)^2 + 4.97(DAHAWT\_WS) - 6.13$ (with $R^2 = 0.9992$)

The DAHAWT generated an average electrical power output of 19.89 W, compared with 6.95 W for the HAWT, corresponding to an improvement of approximately 186%. The high coefficient of determination obtained for the DAHAWT indicates that the fitted curve closely followed the measured power-output data within the observed wind-speed range. These results demonstrate that diffuser augmentation was associated with improved conversion of captured wind energy into usable electrical power.

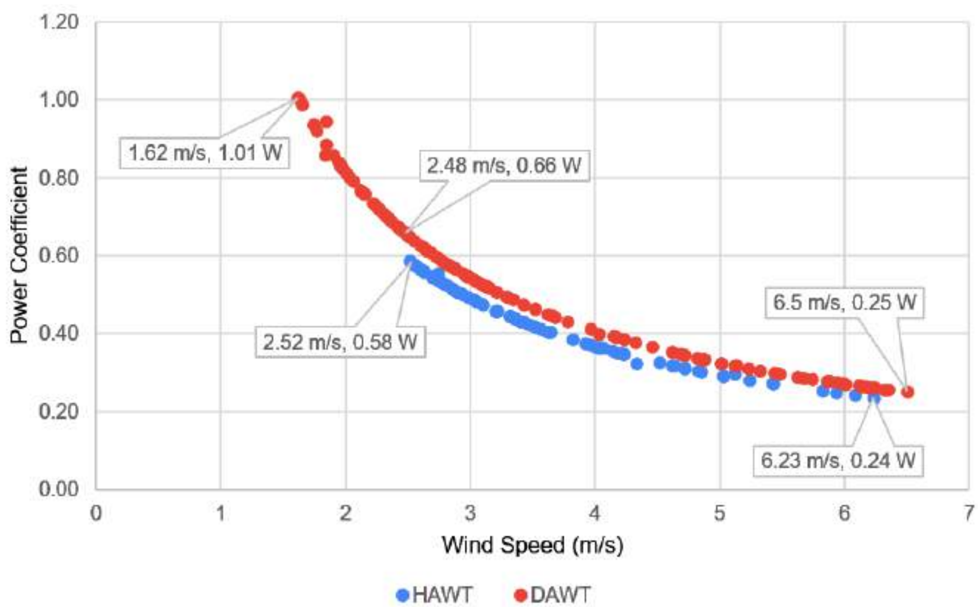
The fitted power-output curves describe the relationship between wind speed and calculated electrical power within the observed field range. The high coefficients of determination indicate that the selected models closely followed the collected data points. These values should not be overextended beyond the measured wind-speed range or treated as independent proof of superior design performance. Instead, they support the measured finding that the DAHAWT produced higher average power output under the tested low-wind conditions.

Power Coefficient Analysis

Because electrical power output alone does not account for variations in the available wind resource, power coefficient analysis was performed to assess the effectiveness of energy conversion for each turbine configuration. Available wind power was estimated using Eq. (2), while the power coefficient was calculated using Eq. (3). The relationship between wind speed and power coefficient is presented in Figure 9.

Figure 9

Comparison of HAWT and DAHAWT in terms of Wind Speed and Power Coefficient



The HAWT exhibited power coefficient values ranging from 0.2364 to 0.5871, with a mean of 0.4364 (SD = 0.1018). In contrast, the DAHAWT achieved values ranging from 0.2509 to 1.0066, with a mean of 0.5603 (SD = 0.2058). Overall, the DAHAWT exhibited a 28.4% higher mean power coefficient than the conventional HAWT.

The maximum power coefficient recorded for the HAWT was 0.5871, which is close to the theoretical Betz limit of 0.593 for conventional unshrouded turbines. The DAHAWT, however, reached a maximum value of 1.0066 when normalized using the diffuser inlet area and measured free-stream wind speed. This value should be interpreted as an apparent or reference-area-based performance coefficient, not as evidence that the rotor itself exceeded the aerodynamic limit for an unshrouded turbine. In diffuser-augmented systems, the shroud and flange alter the flow field by increasing the mass flow rate through the rotor and creating local airflow conditions that differ from the free stream. As a result, performance coefficients above unity may be obtained depending on the reference area and velocity basis used in the calculation. The result therefore indicates the strength of the diffuser-induced augmentation effect rather than a violation of the Betz limit. This interpretation is consistent with diffuser-augmentation and wind-lens studies that emphasize the reference-area dependence of power coefficient in shrouded turbine configurations (Hansen et al., 2000; Ohya & Karasudani, 2010; Al-Quraishi et al., 2019).

Accordingly, the $\mathbf{C_P}$ values reported in this study are most appropriately used for comparative evaluation between the HAWT and DAHAWT configurations tested under the same field conditions. Direct comparison with conventional unshrouded turbine efficiency should be made with caution unless identical reference areas, flow measurements, and aerodynamic definitions are applied.

The scatter plot further indicates that the DAHAWT maintained higher power coefficient values throughout most of the measured wind-speed range, particularly under low-wind conditions. This trend indicates that the diffuser-augmented configuration achieved higher reference-area-based conversion performance across much of the measured wind-speed range. The higher power coefficients observed in the DAHAWT are consistent with the corresponding improvements in rotor speed and electrical output.

Overall Performance Synthesis

Taken collectively, the experimental findings indicate that the DAHAWT outperformed the conventional HAWT across the measured aerodynamic and electrical indicators during the field-testing period. The primary basis for this comparison lies in the observed differences in cut-in wind speed, RPM, voltage, current, power output, power coefficient, and charging occurrence under paired field conditions. These findings support the potential of diffuser augmentation for improving small-scale wind-turbine performance in low-wind environments, subject to the site-specific and short-duration limitations of the study.

CONCLUSIONS AND RECOMMENDATIONS

The results indicate that diffuser augmentation improved the measured aerodynamic and electrical performance of the tested small-scale wind turbine under the low-wind field conditions of the study site. Relative to the conventional HAWT, the DAHAWT demonstrated lower cut-in wind speed, higher rotational speed, higher electrical output, higher reference-area-based power coefficient, and more frequent battery-charging occurrence during the observation period.

From an engineering perspective, the observed improvements were substantial within the measured operating range. The DAHAWT reduced the cut-in wind speed by approximately 35–40%, achieved a maximum rotational speed of 973 RPM compared with 682 RPM for the HAWT, and produced a maximum voltage output of approximately 19.7 V compared with 13.82 V. Mean current output increased from 0.813 A to 1.645 A, while average electrical power output increased from 6.95 W to 19.89 W. The diffuser-augmented configuration also recorded a 28.4% higher mean reference-area-based power coefficient and entered battery-charging mode seven times more frequently than the conventional turbine. These findings suggest that diffuser augmentation can improve the operational response of small-scale wind turbines in similar low-wind settings, although the results should be interpreted within the site-specific and short-duration nature of the field test.

This study contributes field-based experimental evidence on the performance of a fabricated DAHAWT under actual Philippine low-wind conditions. Its main value lies in linking the expected aerodynamic effect of the diffuser with measured startup behavior, rotational response, electrical output, and charging occurrence. However, the findings should be viewed as localized performance evidence rather than a definitive assessment of long-term deployment, commercial feasibility, or year-round energy yield.

Several limitations should be recognized in interpreting the results. The investigation was conducted over a limited observation period at a single field site; therefore, it did not capture seasonal wind variation, long-term operational reliability, structural durability, or performance under a wider range of loading and environmental conditions. The study also did not include detailed techno-economic analysis, lifecycle costing, long-term energy-yield assessment, or commercial feasibility evaluation. In addition, cumulative ampere-hour delivery, continuous battery state-of-charge progression, and extended storage performance were not directly monitored. For these reasons, conclusions regarding large-scale deployment, long-term economic viability, and sustained field reliability should be treated as areas for further investigation rather than final claims.

Future work should therefore include longer monitoring periods, repeated field trials at additional sites, and testing under different wind directions, seasonal conditions, electrical loads, and battery states of charge. Further refinement of diffuser geometry and structural configuration is also recommended to determine whether the observed performance gains can be improved or maintained under broader operating conditions.

Advanced aerodynamic studies using Computational Fluid Dynamics (CFD), Particle Image Velocimetry (PIV), smoke-flow visualization, and wind-tunnel testing may also be conducted to examine airflow acceleration, pressure distribution, vortex formation, and turbulence behavior within the diffuser. These methods would provide stronger physical validation of the mechanisms inferred from the field results.

Finally, future research should include techno-economic assessment, lifecycle costing, maintenance analysis, and long-term energy-yield evaluation to determine whether the additional fabrication and maintenance requirements of diffuser augmentation are justified by the corresponding gains in energy production. Integration with complementary renewable-energy systems, such as solar photovoltaic or small-scale hydroelectric systems, may also be explored for rural and semi-urban applications where wind resources are limited and variable.

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DECLARATION ON THE USE OF AI TOOLS

Artificial intelligence (AI)-assisted tools were utilized only to a limited extent (approximately 10%) for language refinement, grammar improvement, and enhancement of manuscript clarity during the preparation of this paper. No AI tool was used for data generation, data analysis, interpretation of results, or formulation of the study's scientific conclusions. The authors remain fully responsible for the originality, accuracy, integrity, and validity of all research contents, findings, analyses, and interpretations presented in this study.

REFERENCES

Agha, A. (2019). *The integration of diffuser augmented wind turbines (DAWT) into the built environment* (Doctoral thesis, Heriot-Watt University). Heriot-Watt University.

Al-Quraishi, B. A., Asmuin, N. Z., Mohd, S. B., Abdal-wahid, W. A., Mohammed, A. N., & Didane, D. H. (2019). *Review on diffuser augmented wind turbine (DAWT)*. *International Journal of Integrated Engineering, 11*(1), 178–206. https://doi.org/10.30880/ijie.2019.11.01.021

Bianchini, A., Bangga, G., Baring-Gould, I., Croce, A., Cruz, J. I., Damiani, R., Erfort, G., Simao Ferreira, C., Infield, D., Nayeri, C. N., Pechlivanoglou, G., Runacres, M., Schepers, G., Summerville, B., Wood, D., & Orrell, A. (2022). Current status and grand challenges for small wind turbine technology. *Wind Energy Science*, *7*(5), 2003–2037. https://doi.org/10.5194/wes-7-2003-2022

Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). *Wind energy handbook* (2nd ed.). Wiley. https://doi.org/10.1002/9781119992714

Castro, M. T., Delina, L. L., & Ocon, J. D. (2024). Transition pathways to 100 % renewable energy in 208 island mini-grids in the Philippines. *Energy Strategy Reviews*, *52*, Article 101315. https://doi.org/10.1016/j.esr.2024.101315

Chen, Y., & Fang, Y. (2015). Design and analysis of small-scale diffuser augment wind turbines. In *Proceedings of the 2015 International Industrial Informatics and Computer Engineering Conference* (pp. 1088–1093). Atlantis Press. https://doi.org/10.2991/iiicec-15.2015.242

Chhetri, R. K., Upadhyay, D. B., & Ghimire, N. (2021). Comparative analysis of diffusers for micro wind turbine. *Nepal Journal of Science and Technology, 20*(2), 103–112. https://doi.org/10.3126/njst.v20i2.45796

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

Dogru, S., & Yilmaz, O. (2024). Extensive design and aerodynamic performance investigation of diffuser augmented wind turbine (DAWT) guided by generalized actuator disc theory. *Renewable and Sustainable Energy Reviews*, *192*, Article 114212. https://doi.org/10.1016/j.rser.2023.114212

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). SAGE Publications.

Hansen, M. O. L. (2015). *Aerodynamics of wind turbines* (3rd ed.). Routledge. https://doi.org/10.4324/9781315769981

Hansen, M. O. L., Sørensen, N. N., & Flay, R. G. J. (2000). Effect of placing a diffuser around a wind turbine. *Wind Energy*, *3*(4), 207–213. https://doi.org/10.1002/we.37

Hu, J.-F., & Wang, W.-X. (2015). Upgrading a shrouded wind turbine with a self-adaptive flanged diffuser. *Energies, 8*(6), 5319–5337. https://doi.org/10.3390/en8065319

International Energy Agency. (2023). *Renewables 2023: Analysis and forecast to 2028*. https://www.iea.org/reports/renewables-2023

Irawan, Y. H., & Harianto, H. (2019). Numerical simulation of the effect of wind velocity on the diffuser augmented wind turbines performance. *Journal of Energy, Mechanical, Material, and Manufacturing Engineering, 4*(2), 73–82. https://doi.org/10.22219/jemmme.v4i2.9931

Kannan, T. S., Muttagi, S., Ali, M. N. M., & Ali, M. S. M. (2013). Design and flow velocity of a diffuser-augmented wind turbine using CFD. *International Journal of Engineering Research and Applications, 3*(6), 117–124.

Katooli, M. H., & Noorollahi, Y. (2022). Shrouded wind turbines: a critical review on research and development. *International Journal of Ambient Energy*, *43*(1), 8775–8787. https://doi.org/10.1080/01430750.2022.2071273

Khalid, W., Sherbaz, S., Maqsood, A., & Hussain, Z. (2020). Design and optimization of a diffuser for a horizontal axis hydrokinetic turbine using computational fluid dynamics based surrogate modelling. *Mechanika*, *26*(2), 161–170. https://doi.org/10.5755/j01.mech.26.2.23511

Lipian, M., Dobrev, I., Karczewski, M., Massouh, F., & Jozwik, K. (2019). Small wind turbine augmentation: Experimental investigations of shrouded- and twin-rotor wind turbine systems. *Energy*, *186*, Article 115855. https://doi.org/10.1016/j.energy.2019.07.151

Maañdal, G. L. D., Tamayao-Kieke, M.-A. M., & Danao, L. A. M. (2021). Techno-economic assessment of offshore wind energy in the Philippines. *Journal of Marine Science and Engineering, 9*(7), 758. https://doi.org/10.3390/jmse9070758

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: Theory, design and application* (2nd ed.). Wiley.

Mathew, S. (2006). *Wind energy: Fundamentals, resource analysis and economics*. Springer. https://doi.org/10.1007/3-540-30906-3

McHugh, M. L. (2013). The chi-square test of independence. *Biochemia Medica, 23*(2), 143–149. https://doi.org/10.11613/BM.2013.018

Montgomery, D. C., Peck, E. A., & Vining, G. G. (2021). *Introduction to linear regression analysis* (6th ed.). Wiley.

Naji, M. M., & Jabbar, B. A. (2024). Diffuser augmented wind turbine: A review study. *AIP Conference Proceedings, 3051*(1), 100015. https://doi.org/10.1063/5.0191895

Ohya, Y., & Karasudani, T. (2010). A shrouded wind turbine generating high output power with wind-lens technology. *Energies, 3*(4), 634–649. https://doi.org/10.3390/en3040634

Ohya, Y., Uchida, T., Karasudani, T., Hasegawa, M., & Kume, H. (2012). Numerical studies of flow around a wind turbine equipped with a flanged-diffuser shroud using an actuator-disk model. *Wind Engineering*, *36*(4), 455–472. https://doi.org/10.1260/0309-524x.36.4.455

Olalo, J., Dela Cruz, C. J., Bilang, R. G., Bonifacio, R., & Paringit, E. (2022). Determination of a potential for the installation of small-scale wind turbine in Barangay Bagasbas, Daet Camarines Norte, Philippines. *ASEAN Engineering Journal*, *12*(1), 17–26. https://doi.org/10.11113/aej.v12.16503

Paranjape, A. D., Bajaj, A. S., Palanganda, S. T., Parikh, R., Nayak, R., & Radhakrishnan, J. (2021). Computational analysis of high-lift-generating airfoils for diffuser-augmented wind turbines. *Wind Energy Science, 6*, 149–157. https://doi.org/10.5194/wes-6-149-2021

Twidell, J., & Weir, T. (2021). *Renewable energy resources* (4th ed.). Routledge. https://doi.org/10.4324/9780429452161

Veers, P., Bottasso, C. L., Manuel, L., Naughton, J., Pao, L., Paquette, J., Robertson, A., Robinson, M., Ananthan, S., Barlas, T., Bianchini, A., Bredmose, H., Horcas, S. G., Keller, J., Madsen, H. A., Manwell, J., Moriarty, P., Nolet, S., & Rinker, J. (2023). Grand challenges in the design, manufacture, and operation of future wind turbine systems. *Wind Energy Science*, *8*(7), 1071–1131. https://doi.org/10.5194/wes-8-1071-2023