Analyzing the Output of a 1 kW Vertical Wind Turbine in Low-Wind Areas: The Case Study of Madina

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ABSTRACT

Wind energy has been at the forefront of the renewable energy transition. Although Horizontal-Axis Wind Turbines (HAWTs) remain the most popular, Vertical-Axis Wind Turbines (VAWTs) have also gained attention, particularly for turbulent and low-wind-speed locations. However, VAWTs face limitations, such as low self-starting capability and low efficiency. This research evaluates the performance of a 1 kW VAWT in Madinah, focusing on the generated parameters like the voltage, current, power, and energy. Previous studies lacked field data that could be used to empirically determine the capacity factor and power coefficient, a gap addressed in this study. Based on the wind data, the region's wind speeds are sufficient for power generation, despite being classified as a low-wind area. The study was divided into two phases, with the first phase recording the voltage and current over 7-8 h (divided into 4 short intervals) of different timings. The second phase derived the power by multiplying the voltage and the current. For energy estimation, wind speed data from a typical windy day in March 2025 were analyzed, yielding approximately 230 kWh/day. The turbine generated an average voltage of 32 V, with variations across wind speeds, achieving a power coefficient of 0.29 with a capacity factor of 15%. The ambient temperature was also recorded, revealing a minimal impact on performance.

Keywords-component; vertical-axis wind turbine; performance analysis; power coefficient; energy; low wind; PVGIS

I. INTRODUCTION

The energy sector's transition from fossil fuels to renewable sources has accelerated significantly. Solar photovoltaic systems dominate the market, growing from 70 GW in 2011 to 1865 GW by 2024 [1]. However, wind energy has gained substantial traction. According to the World Wind Energy Association (WWEA), global wind turbine installations surged from 371 GW in 2014 to 1174 GW in 2024 [2]. Wind energy not only meets the rising global demand but also mitigates environmental issues, such as global warming, by replacing fossil fuels.

Wind turbines convert the kinetic energy of the wind to electrical energy via generator rotation coupled with blade movement [3]. This is the reason for the significance of wind speed in wind energy generation [4]. Turbines are typically installed offshore, onshore, and on rooftops. Based on the abundance of wind speeds, obstacle interferences with buildings and other landscapes, the proper turbine installation type is chosen. Rooftops are considered for installation, usually in urban areas, but they are characterized by lower wind speeds, high turbulence, and obstructions.

Wind turbines have two main designs with respect to the rotor's axis of rotation: the HAWT and VAWT, the configurations of which can be found in [5, 6]. Table I compares these designs [7], highlighting the advantages of VAWTs, such as easier installation, compact configuration, and omnidirectionality [8].

TABLE I. COMPARISON BETWEEN HAWT AND VAWT

Parameters	**HAWT**	**VAWT**
Nominal wind speed	Lower	Higher
Installation altitude	Higher	Lower
Aerodynamics efficiency	Higher	Lower
Tip speed ratio	Up to 14.3 per blade	Rise to 5.1
Site selection	Onshore, offshore, outskirt areas	Onshore, offshore, urban areas
Wind direction	Single direction	Omnidirectional
Capacity	High, up to 20 MW	Low, up to 6 MW
Noise	Higher	Lower
Acting force	Lift force	Lift force/ drag-based
Yaw control	Necessary	Not required
Size & weight	Higher	lower
Efficiency	50%	40%
Stress and maintenance	Higher	Lower
Durability	Low	High
Turbulent tolerance	Not suitable	Suitable for turbulent wind

HAWTs are more common, with three-bladed turbines being the most popular owing to their balanced torque design. VAWTs, such as Savonius and Darrieus (invented in 1920) [9], have several advantages, including the ability to capture wind from all directions, low acoustic noise, and less upset gravity. However, they suffer from low self-starting and power efficiency [9, 10]. One of the challenges that face/encountered in wind energy generation is the turbulent wind intensity [11]. This happens mainly due to the terrain of the area, wind shear, and building obstructions. VAWT is the most suitable turbine design for areas with such conditions, and was chosen in the current study. Generally, the Arabian Peninsula has average wind speeds in the range of 2-6 m/s and can be characterized as a low-wind region [3]. Madinah experiences low wind speeds and is subsequently classified as a low-wind region. Several studies have been conducted on the performance and improvement of VAWTs. Authors in [12] reviewed the performance of VAWTs. As for the Madinah region, authors in [4] assessed its wind resources using the Weibull distribution. They found that the average wind speed was 3.467 m/s. Using an Aventa AV-7 wind turbine, an annual energy output of 8648 kWh at a rated speed of 7 m/s was estimated. As shown in the short literature review in Table II, prior studies either focused on HAWTs [3] or simulated VAWT performance [9, 10], leaving a gap for empirical VAWT data in low-wind desert regions such as Madinah. The present study bridges this gap by providing field measurements of a 1 kW H-Darrieus VAWT, demonstrating its feasibility despite the city's low average wind speeds (3.5–5 m/s). Additionally, this study proposes hybrid wind-PV systems to mitigate intermittency, a solution that has not been addressed in earlier studies.

TABLE II. METHODOLOGY AND KEY FINDINGS COMPARISON

Reference	**Location**	**Methodology**	**Key findings**	**Limitations/gaps**	**This study's Contribution**
[4]	Madinah, Saudi Arabia	Weibull distribution, Aventa AV-7 HAWT	Estimated 8648 kWh/year at 7 m/s rated speed	No VAWT field data; overestimated for low-wind reality	First VAWT field measurements (230 Wh/day at 3.5–5 m/s) in Madinah
[3]	Low-wind regions (generic)	Hybrid experimental-theoretical	Achieved 215–223 W output for micro-HAWTs	Focused on HAWTs; ignored VAWT urban advantages	VAWT-specific analysis for desert urban settings with turbulence
[9]	Literature review	Meta-analysis of VAWT designs	Identified low self-starting efficiency (~1.5 m/s threshold)	Lack of real-world validation in arid climates	Empirical proof of H-Darrieus startup at 1.5 m/s in Madinah
[11]	Turbulent wind conditions	CFD simulation of dual-VAWT	Turbulence reduces efficiency by 15%	Simulated idealized conditions; no desert data	Field evidence of VAWT tolerance to Madinah's turbulent winds
[13]	Low-wind regions	CDF method	TSR of 2.5 revealed the optimal power	Limited to Indian climatic data	Included the study area data

II. CASE STUDY AREA

Nestled in the vast Arabian Desert, Madinah experiences a desert climate characterized by extreme temperatures. The city's geographical coordinates place it inland, away from coastal influences, contributing to arid conditions. The landscape surrounding Madinah is typical of a desert environment, marked by sandy terrain and sparse vegetation.

The region has considerable wind speed with seasonal variations. Figure 1 displays the average wind speed of the region for every month over a period of 15 years, as recorded by the Photovoltaic Geographical Information System (PVGIS) [14]. The average wind speed is around 4.5-5 m/s, with some peaks at March-May. In general, during winter, the region experiences reliable wind speeds of about 4 m/s. Given these conditions, VAWT is well-suited for the region.

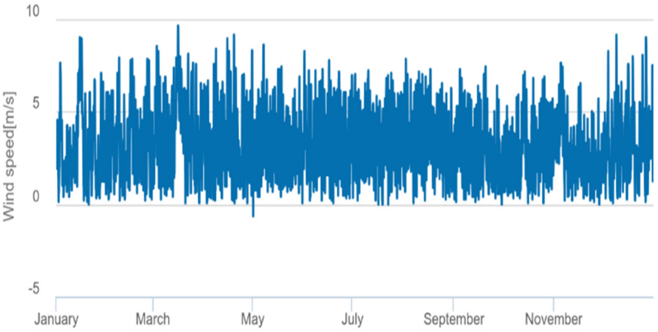

Fig. 1. Annual average wind speed.

III. MATERIALS AND METHODOLOGY

The study used a 1 kW H-Darrieus turbine VAWT installed at the Islamic University of Madinah. The turbine parameters are listed in Table III. The most important factor for wind generation is the wind speed. Hence, the wind speed data were sourced from PVGIS, NASA, and the Saudi National Center for Meteorology. To avoid conflict in the data assessment, the study used meteorological data from the Saudi National Center for Meteorology, which is the national database for the case study area owing to its considerable accuracy. Figure 2 illustrates the daily distribution of the wind speed.

The performance of this turbine is evaluated, focusing on the effect of the low wind speed on the generated energy. Based on this analysis, the current research presents the feasibility of generating wind energy in the area, advantages, disadvantages, and challenges.

The turbine was connected to a hybrid wind and solar controller (HY-C10-48BSLS). A 1.5 kW pure sine wave inverter and a battery system (48 V, 200 Ah) were connected to the system through the controller.

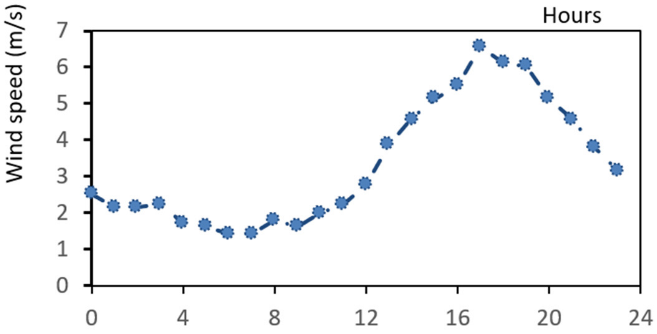

Fig. 2. Daily wind speed distribution in the study region.

TABLE III. AEOLUS VERTICAL WIND TURBNINE

Parameters	Values
Rated power	1 kW
Output voltage	48 V
Rotor height	2.8 m
Rotor diameter	2.0 m
Start-up wind speed	4.5 m/s
Rated wind speed	10 m/s
Generator efficiency	0.96
Lifetime	20 years

The performance parameters were recorded using a DAQ6510 Acquisition/Multimeter System with thermocouples as the connecting medium. The voltage was measured directly, and the current was sensed using a Hall-effect sensor (LA 55-P). The ambient temperature was also monitored.

The parameters were recorded for a period of almost 8 h, subdivided into four short periods of 2 h. The short periods were taken at different hours of the day. Afterwards, the data generated were merged for a complete assessment.

IV. THEORETICAL CALCULATIONS

The power coefficient is a measure of a wind turbine's efficiency. It represents the fraction of the wind's kinetic energy that the turbine's rotor can capture and convert into mechanical energy by considering a rated wind speed of 10 m/s. Based on the rated values of the turbine, the power generated by the VAWT is given by:

$$P_{wt} = \frac{1}{2}\rho A v^3 C_p \tag{1}$$

where P_{wt} is the generated power, ρ is the air density (1.225 kg/m^3), A is the blade area (height × diameter), v is the wind speed, and C_p is the power coefficient.

Solving for C_p we get:

$$C_p = \frac{1000}{0.5 \times 1.225 \times (2 \times 2.8) \times 10^3} = 0.29$$

Similarly, the energy generated by the VAWT is given by:

$$E_{wt} = P_{rated} Operating\ hours \tag{2}$$

Therefore, the expected daily rated energy is 1 kW × 24 h = 24 kWh. Intuitively this is not realistic, due to the variation of the wind speed, the rated energy cannot be generated entirely. Therefore, the Capacity Factor (*CF*) is introduced. *CF* is simply a factor for measuring the effectiveness of a generating system, using the ratio of the exact generated energy to the maximum possible energy to be generated. The CF is given by:

$$CF = \frac{Actual\ output}{Maximum\ output} \tag{3}$$

The rated energy can be harnessed only when the rated wind speed is available, i.e., 10 m/s. Considering the wind speed, the CF is:

$$CF = \left(\frac{actual\ wind\ speed}{rated\ wind\ speed}\right)^3 \tag{4}$$

V. EXPERIMENTAL SETUP

To achieve the objectives, an experimental setup was staged. The 1 kW – VAWT model and H-Darrieus type by AEOLOS wind turbine was installed on the rooftop of the engineering faculty at approximately 14 m. Figure 3 depicts the installed wind turbine and the entire experimental setup. The H-Darrius VAWT is shown in Figure 3(a). The turbine is connected to the hybrid controller (Figure 3(c)), which controls the charging of the battery and the inverter supply. The battery and inverter were connected at the bottom of the controller, as illustrated in Figure 3(e). The current was measured using the current sensor shown in Figure 3(b). Both the current and voltage were logged into the data acquisition device, as portrayed in Figure 3(f). To power the current sensor circuit, the power source displayed in Figure 3(d) was used.

Data logging is essential for real-time data analysis. Various parameters were recorded using a combination of sensors and a data acquisition tool. To assess the performance of this turbine, thermocouples, which act as signal conductors, were used as connectors between the input of the controller coming from the turbine as output and the data-logging device. The data-logging tool used for the study was a 40-channel data acquisition/multimeter system from Keithley Tektronic Company (DAQ6510).

The following parameters were recorded:

1. AC voltage: Ideally, the wind turbine generates AC voltage, to measure the incoming voltage, the DAQ6510 was used, with the help of thermocouples.
2. Incoming current: The primary (input) current I_P is sensed and converted into a secondary current I_S, which is then measured as a voltage across a burden resistor R_M. Figure 4 shows the current sensor circuit employed to convert the physical current into measurable signal for the DAQ system [15]. A ±15 V voltage source was connected to the $\pm U_C$, and a 100 Ω resistor was used as the R_M. The primary conductor was then passed through the aperture of the sensor. Hence, to assess the current, the voltage across the R_M was measured and divided by the R_M.
3. Temperature: The ambient temperature was also considered to determine whether the surrounding temperature influenced the turbine performance, providing insights into how the performance might vary under different weather conditions.

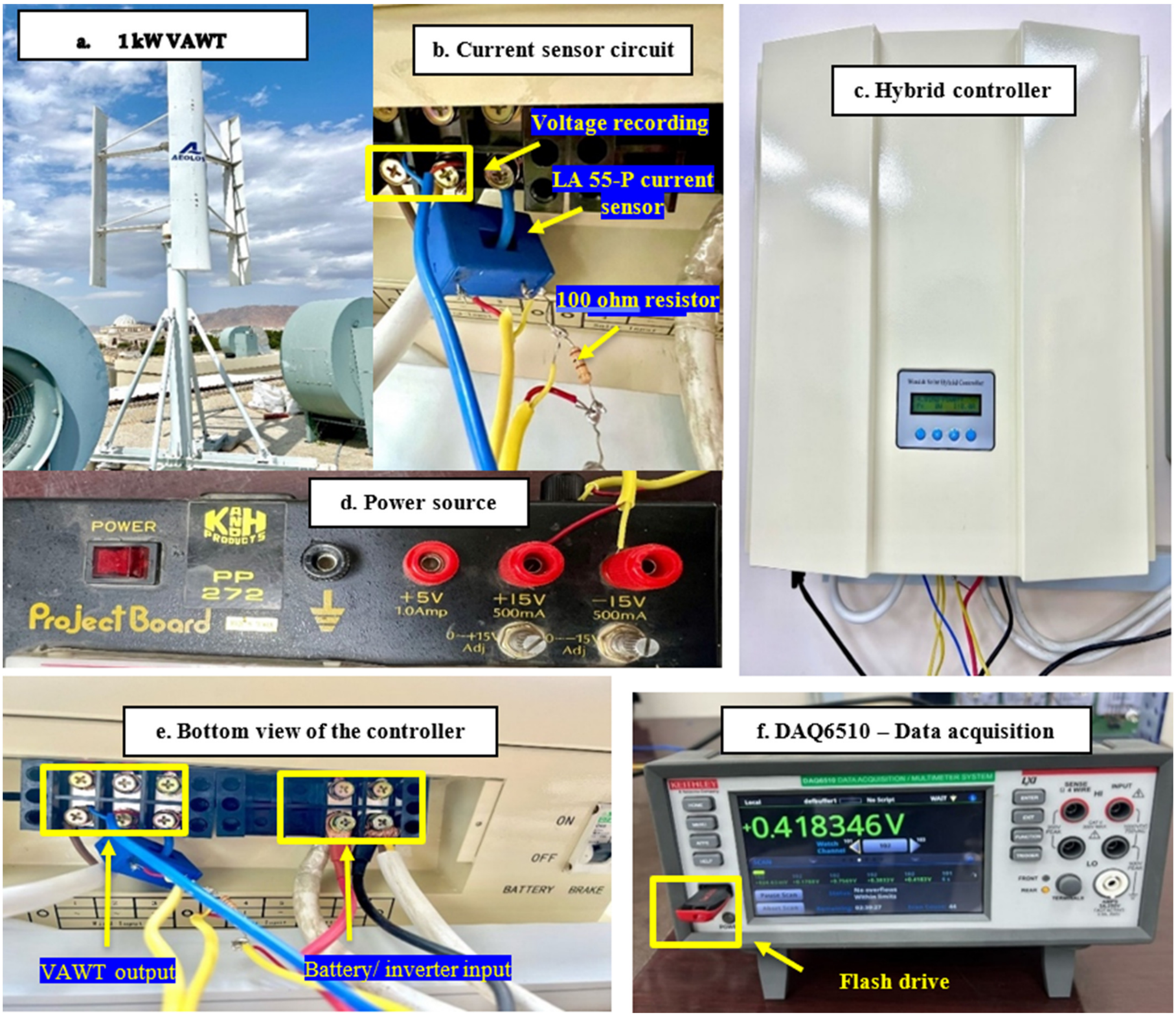

Fig. 3. The experimental setup used in this study.

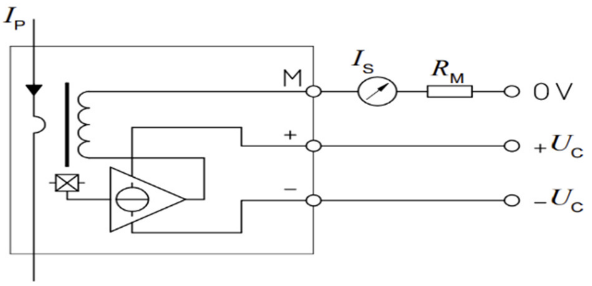

Fig. 4. Current sensor circuit.

VI. RESULTS AND DISCUSSION

The results from the experiment provided considerable data with respect to the incoming voltage and current. Figure 5 illustrates the recorded current and voltage. The voltage and current values decreased drastically at around 175-262 due to the drastic drop in the wind speed. Now, based on the current and voltage data, the power can be deduced by multiplying the two, as shown in Figure 6.

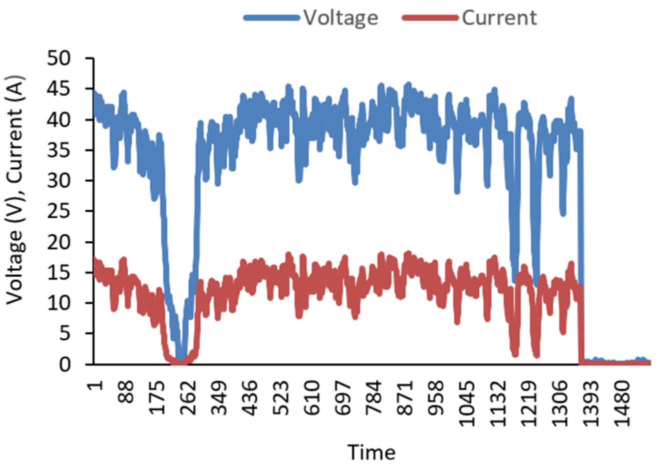

Fig. 5. Recorded voltage and current.

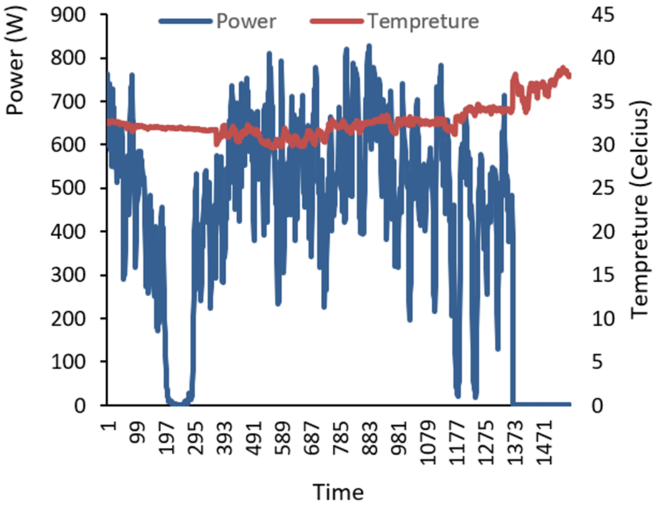

Fig. 6. Power generated along with temperature.

As presented in Figure 6, the temperature has negligible impact on the generated power. Nevertheless, extreme temperatures usually come with lower wind speeds, which, by extension, can affect power generation. Furthermore, to determine the power and energy generated, (1) and (2) were used. The energy is the rate at which power flows. Equation (2) defines the energy generated. For a better energy assessment, the wind speed for a single day in March, one of the windy months, was used to observe the energy generated per day. The *CF* was determined using (4), and the overall energy equation is given by (5). The results are shown in Figure 7.

$$E_{wt} = P_{measured} \times Operating\ hours \times CF \qquad (5)$$

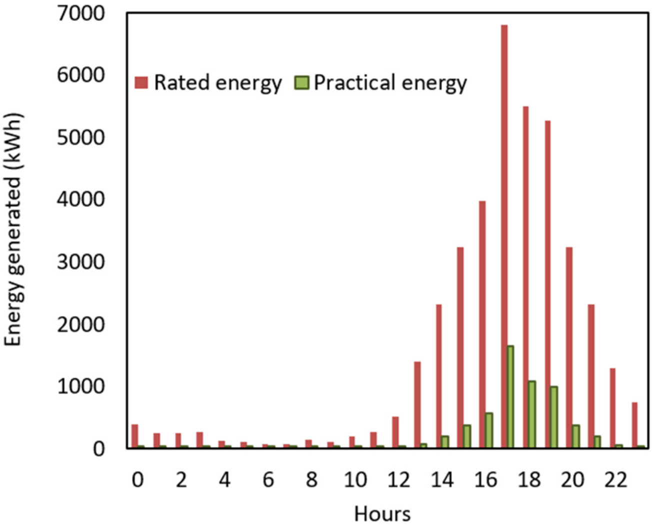

Fig. 7. Estimated rated energy versus the exact practical energy per day.

VII. CONCLUSIONS

Based on the results obtained in this study, the studied Vertical-Axis Wind Turbine (VAWT) produced a considerable amount of power over the time recorded, with an average of 413 W. Although the site experiences low wind speeds, a significant amount of voltage (average of 31 V) and current (10.5 A average) was observed. Similarly, with regard to the energy produced, based on the data recorded, the turbine can generate an average of 230 kWh/day. The turbine rotated at an average of 40-65 RPM for the best results. Compared to previous studies, this study achieved a Capacity Factor (*CF)* of approximately 15%, which is more realistic for VAWTs in low-wind regions.

Although the results are promising, the system can be improved by scaling it to a wind farm. Similarly, another improvement can be achieved by increasing the height of the rotor installation. Taller wind turbines produce more energy, although this might come with the heavy price of high installation and maintenance costs.

Finally, it is essential to note that wind turbines depend solely on the availability of significant wind speeds. However, the wind speed is variable across the year as well as the hours of the day. This variability gives rise to the intermittency of wind energy. Hybridizing wind energy with solar PV will not only solve the intermittency problem but also increase renewable energy penetration. Incorporating storage systems, such as batteries, will also assist.

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