EJSIT
European Journal of Science, Innovation and Technology
ISSN: 2786-4936
www.ejsit-journal.com
Volume 6 | Number 3 | 2026

Data-Driven Assessment of Low-Speed Wind Energy Harvesting Potential Using MATLAB/Simulink Modeling

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ABSTRACT

This study presents a data-driven evaluation of a wind energy harvesting system designed for low power applications, particularly wireless sensor networks (WSNs). High resolution wind speed data were collected over a one-year period from January-December 2025 at the Federal University of Petroleum Resources, Effurun (FUPRE), Nigeria, using a calibrated Automated Weather Observing Station (AWOS). A comprehensive system model was developed in MATLAB/Simulink, incorporating aerodynamic wind turbine dynamics, electromagnetic energy conversion, rectification, DC-DC conversion, maximum power point tracking (MPPT) using the perturb and observe (P&O) algorithm, and a power management system (PMS) with battery storage. Simulation results reveal strong seasonal variations in harvested power, with peak performance observed in March, where average DC-DC output reaches approximately 38.022 mW and daily harvested energy peaks at about 0.766 Wh/day. Lower performance is recorded during periods of reduced wind activity, particularly between October and November. Despite these fluctuations, the PMS effectively regulates power flow, ensuring stable energy delivery to the load. The system demonstrates a relatively constant efficiency of approximately 16.47% across all months, indicating stable internal conversion performance. Overall, the results confirm the feasibility of utilizing low-speed wind energy for continuous power supply in autonomous systems. The study highlights the effectiveness of integrating real environmental data with intelligent power management strategies to enhance reliability and energy utilization in wind energy harvesting applications.

Keywords: Wind energy harvesting, Wireless Sensor Networks, IoT Power Supply, Small-Scale Wind Turbine, Data-Driven Assessment

1. INTRODUCTION

Energy harvesting is the process in which energy from the environment is transformed into usable electrical energy (Hamina *et al.,* 2020: Rajanbabu *et al.,* 2020). Energy harvesting system are classified into two types based on their energy sources as; ambient and external sources. Ambient sources such as solar, wind, RF, biomass are present in the environment free of charge and permanent, while external sources such as pressure, body movement, induction, vibration are not permanent and deployed explicitly for the purpose of energy scavenging (Jaspreet *et al.,* 2020). Energy harvesting approaches are generally classified into two categories: (1) systems that convert ambient energy directly into electrical power for immediate use in wireless sensor networks without storage, and (2) systems that first store the harvested energy before delivering it to the wireless sensor networks (Shaikh & Zeadally, 2016).

Wireless Sensor Networks (WSNs) are large number of static sensor nodes with limited processing and power capabilities that are deployed in a distributed manner and communicate over unreliable, short-range radio links or gateway (Shaikh *et al.,* 2013; Alexander *et al.,* 2021). WSNs is a type of convenient sensor nodes which is used for monitoring and transmitting data

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continuously allowing users to remotely view the operating status of machine, and other devices at the user facilities (Khazaee *et al.,* 2019; Shafiq *et al.,* 2019). A WSNs is comprised of nodes which may amount from a few to several hundreds or even thousands, where each node is connected to one sensor (Apurva, 2022). Each sensor node consists of a sensing unit, processing unit, communication unit, power supply unit usually a battery or some form of energy harvester, and optionally a positioning and mobility system (Obbo, 2022). WSNs finds application in various areas like military, environmental monitoring and disaster management, transportation, flora and fauna, health, security, energy, industry, smart homes, and other commercial purposes (Gupta & Kumar, 2013; Onuekwusi *et al.,* 2015).

Despite the widespread applications of WSNs, it is well-known that one of the major challenge faced with WSNs is limited energy supply to sensor node (Shaikh *et al.,* 2015; Ahmad *et al*., 2019; Iftikhar *et al.,* 2021; Divyanshu *et al.,* 2024). The key requirement of a WSNs is that it should be autonomous, operate for a particular time, and require little maintenance which can be costly and inconvenient depending on the number of nodes and the application itself which could necessitate nodes with limited accessibility (Panatik *et al.,* 2016). Batteries remain the primary energy source for sensor nodes; however, they are associated with several limitations and challenges (Raquib *et al.,* 2016). First, severe weather conditions may break down the batteries, resulting in chemical leakages that can cause various environmental problems (Tiliute, 2007). Secondly, batteries are insufficient in providing enough energy for long term applications, which lead to inconvenient frequent charging or replacement (Penella *et al*., 2009; Katrina *et al.,* 2021). Finally, in applications where wireless sensor networks are deployed in hard to reach locations, replacing or recharging batteries is often impractical. Therefore, the system should be designed to ensure that the available battery capacity can support operation over its intended lifetime. (Sichitiu & Dutta, 2005; Abd Aziz *et al.,* 2012). Of course, a possibility is to use higher capacity batteries to ensure the required energy constraints are met, but this result in increased size for the device that is often not acceptable (Marco, 2021).

Though the energy efficiency and expected lifetime of WSNs has increased over the last few years due to sensor and software optimizations, lightweight communication protocols, and low-power radio transceivers, energy supply remains a major challenge with WSNs (Keh *et al.*, 2011; Prauzek *et al.,* 2018; Zhou *et al*., 2019; Wang *et al.,* 2019).

Energy harvesting has gained significant attention as an effective approach for overcoming the energy limitations associated with wireless sensor networks (Choudhary *et al*., 2020; Fadoua & Adil, 2022; Hussain *et al*., 2024; Muhammad *et al*., 2025).

2. METHODOLOGY

2.1 Experimental Data Collection

Wind speed data used in this study were obtained from Federal University of Petroleum Resources, Effurun (FUPRE), Delta State, Nigeria (geographical coordinates: approximately 5.65°N, 5.62°E). The data acquisition was carried out using the institution’s installed Automated Weather Observing Station (AWOS), strategically located in close proximity to the College of Science building to ensure reliable and representative atmospheric measurements.

The AWOS system is equipped with calibrated meteorological sensors capable of providing high-resolution, continuous wind speed measurements under real environmental conditions. For this study, wind speed data were recorded over a complete annual cycle, spanning from January 2025 to December 2025. Measurements were sampled at regular intervals of 20 minutes throughout each day, thereby capturing both daily variations and seasonal fluctuations in wind behavior.

This high temporal resolution dataset enables a detailed characterization of the wind resource, including temporary atmospheric changes and short-term variability that are critical for accurate energy harvesting analysis. The use of long-term, site-specific measurements ensures that the dataset reflects the true wind profile of the study location, providing a reliable foundation for subsequent modeling and performance evaluation of the wind energy harvesting system.

2.2 System Architecture

The conceptual model of the Wind Energy Harvesting System adopted in this work is presented in Figure 1. It is designed to convert kinetic energy from ambient air flow into electrical power for sustaining a wireless sensor node in remote or off-grid applications where consistent wind resources are available.

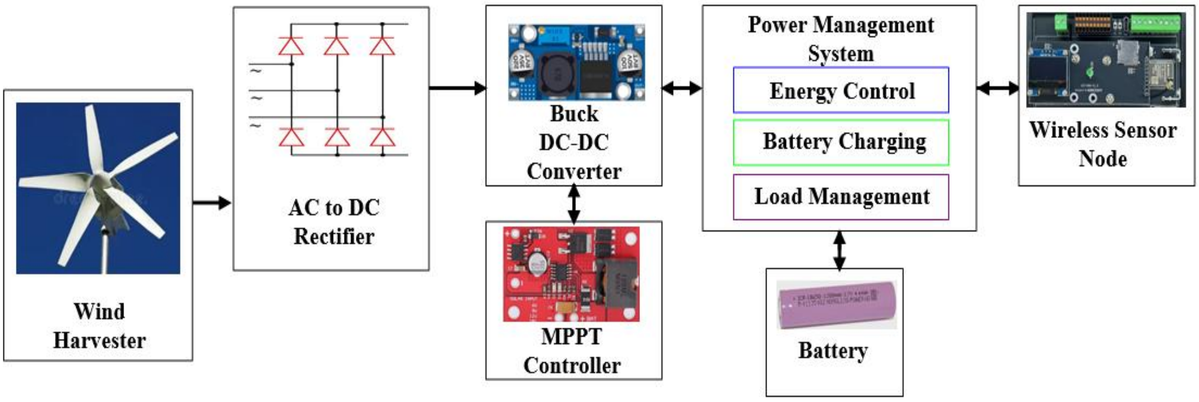

Figure 1: Architecture of the Wind Energy Harvester

The system comprises a small-scale wind turbine that extracts mechanical power through rotating blades, an alternating current (AC) to direct current (DC) rectifier circuit that converts the generator's AC to DC, a DC to DC buck converter that steps down and regulates the voltage, a maximum power point tracking controller that optimizes the operating point for peak extraction, a power management system that ensures efficient distribution and protection, a battery that stores surplus energy for use during low-wind periods, and a wireless sensor node that consumes the power for data acquisition and wireless communication.

2.3 Modeling of a Wind Energy Harvesting system

This model is derived from first principles starting with fluid dynamics for turbine aerodynamics advancing through rotational mechanics, electromagnetic induction, diode rectification, DC-DC buck converter, MPPT control, PMS, battery and load.

2.3.1 Modelling of the Wind Energy Harvester

The kinetic energy of wind is a function of wind speed, the specific mass of air, the area of air space where the wind is captured and the height at which the rotor is placed. The power available in a uniform wind field is given by Equation (1) as (Tigilu & Mukhdeep, 2018):

$$P_{wind} = \frac{1}{2} A \rho V^3 \tag{1}$$

where P_{wind} is the power available in the wind, A is the sweep area of the turbine blades (m^2), ρ is the air density (kg/m$_3$), and V is the wind speed (m/s).

The mechanical power produced by a wind turbine is relative to the rotor swept area, wind speed, rotor speed and power coefficient (C_p). Power coefficient describes how efficiently a wind turbine converts wind energy into mechanical energy. The power coefficient is defined as the ratio of the mechanical power P_m generated by the system to the total wind power P_w available across the turbine's swept area, as expressed in Equation (2) as (Tigilu & Mukhdeep, 2018):

$$C_p = \frac{P_{mech}}{P_{wind}} \tag{2}$$

where C_p is the power coefficient, P_{mech} is the mechanical power produced by the turbine, P_{wind} is the total power available in the wind.

The mechanical power (P_{mech}) extracted by the wind turbine from the kinetic energy of air flow through the rotor swept area based on momentum theory and the Betz limit and is calculated using Equation (3) as (Loan *et al.*, 2023):

$$P_{mech} = \frac{1}{2} A\rho V^3 C_p(\lambda, \beta) \tag{3}$$

where λ is the tip-speed ratio, and β is the blade pitch angle (^{o})

Power coefficient is the measure of the efficiency of wind turbine, a nonlinear function of operating tip-speed ratio (TSR), and pitch angle. The tip-speed ratio (λ) is described as the ratio of the tangential velocity of the blade tips (machine's rotational speed) divided by the effective wind speed. The TSR depends on both the wind speed and the rotational speed of the rotor expressed in Equation (4) as:

$$\lambda = \frac{\omega_r R}{V} \tag{4}$$

where ω_r is the rotor speed (rad/s), and R is the rotor radius (m).

The aerodynamic torque (τ_{aero}) generated on the rotor shaft is derived from power-torque equivalence in rotational systems where torque is power divided by angular velocity from Newton's laws applied to rotation given by Equation (5) as:

$$\tau_{aero} = \frac{P_{mech}}{\omega} = \frac{1}{2} \rho A v^2 r C_t(\lambda, \beta) \tag{5}$$

where ω is the angular speed (rad/s), r is the blade radius (m), $C_t = C_p/\lambda$ is the torque coefficient reflecting blade aerodynamics.

Rotor dynamics model the transient response to varying torque incorporating inertia friction and generator loading from Euler's rotational equation. From Equation (5) the angular acceleration is given by Equation (6) as:

$$J\frac{d\omega}{dt} = \tau_{aero} - \tau_{gen} - B\omega \tag{6}$$

where J is total moment of inertia in (kg^2m), $\frac{d\omega}{dt}$ is the rate of change of angular speed, ω is the angular speed of turbine (rad/s), τ_{aero} is the aerodynamics torque from the wind, τ_{gen} is electromagnetic torque from the generator, and $B\omega$ is damping coefficient in (Nms/rad) accounting for mechanical losses.

The generator typically a permanent magnet synchronous machine induces voltage through Faraday's law as magnets rotate past stator coils. The induced electromotive force per phase (e_{phase}) is given by Equation (7) as:

$$e_{phase} = N\phi\omega \sin(p\theta/2) \tag{7}$$

where N is number of turns, ϕ magnetic flux in (webers), p is pole pairs, θ is electrical angle leading to three-phase alternating current output with root-mean-square (rms) voltage $V_{ac,rms} = k_e\, \omega / \sqrt{2}$ and k_e is a machine constant around 0.2 V/rad/s.

2.3.2 Modeling the Alternating to Direct Current Rectifier

The alternating current to direct current rectifier, a full-bridge diode circuit converts the alternating voltage to pulsating direct current using unidirectional diode conduction from p-n junction physics. The average DC voltage is given by Equation (8) as:

$$V_{dc,rect} = \frac{3\sqrt{6}}{\pi} V_{ac,rms} - 2V_d \tag{8}$$

where $V_{dc,rect}$ is the output DC after rectification, $\frac{3\sqrt{6}}{\pi}$ is the constant for converting AC to DC (rectifier factor), $V_{ac,rms}$ is the RMS value of the AC input voltage, $2V_d$ is the total voltage drop (0.7 V) across two diodes in conduction.

2.3.3 Modeling the DC to DC Buck Converter

The DC-DC buck converter steps down the rectified voltage to battery levels with duty cycle control. The voltage at the output (V_{out}) is given by Equation (9) as:

$$V_{out} = DV_{dc,rect} \cdot \eta_{buck} \tag{9}$$

where V_{out} is the output voltage for the DC-DC buck converter, D is the duty (fraction of time the MOSFET was switched ON), $V_{dc,rect}$ is the input DC voltage from the rectifier, and η_{buck} is the efficiency of the buck converter.

2.3.4 Modeling the Maximum Power Point Tracking Circuit.

The P&O method works by making small adjustments to the duty cycle and monitoring the corresponding variation in output power. The instantaneous power is given by Equation (10) as:

$$P(k) = V(k) \,.\, I(k) \tag{10}$$

The changes in power and voltage are computed using Equation (11) and (12) as:

$$\Delta P = P(k) - P(k\text{-}1) \tag{11}$$

$$\Delta V = V(k) - V(k\text{-}1) \tag{12}$$

Based on these variations, the duty cycle is updated according to Equation (13) as:

$$D(k+1) = \begin{cases} D(k) + \Delta D, & \text{if } \Delta P > 0 \text{ and } \Delta V > 0 \\ D(k) - \Delta D, & \text{if } \Delta P > 0 \text{ and } \Delta V < 0 \\ D(k) - \Delta D, & \text{if } \Delta P < 0 \text{ and } \Delta V > 0 \\ D(k) + \Delta D, & \text{if } \Delta P < 0 \text{ and } \Delta V < 0 \end{cases} \tag{13}$$

where $\Delta D$is a small perturbation step. This iterative process ensures that the operating point converges toward the maximum power point.

2.3.5 Modeling the Power Management System.

The power management system allocates power with overcurrent protection from feedback controls. Managed power (P_{pms}) is given by Equation (14) as:

$$P_{pms} = \eta_{pms} P_{out} \tag{14}$$

where η_{pms} is the efficiency of the PMS, P_{out} is the total output power available from the energy source before PMS losses.

2.3.6 Modeling the Battery Storage.

Battery storage accumulates through electrochemical charging. Stored power (P_{stored}) is given by Equation (15) as:

$$P_{stored} = \eta_{charge} P_{pms} \tag{15}$$

where η_{charge} is the charging efficiency of the system.

2.3.7 Modeling the Wireless Sensor Node.

The wireless sensor node consumes with duty cycling. The system efficiency (η_{system}) is given by Equation (16) as:

$$\eta_{system} = P_{stored}/(\tfrac{1}{2}\rho A v^3) \tag{16}$$

where P_{stored} is the power delivered to the load.

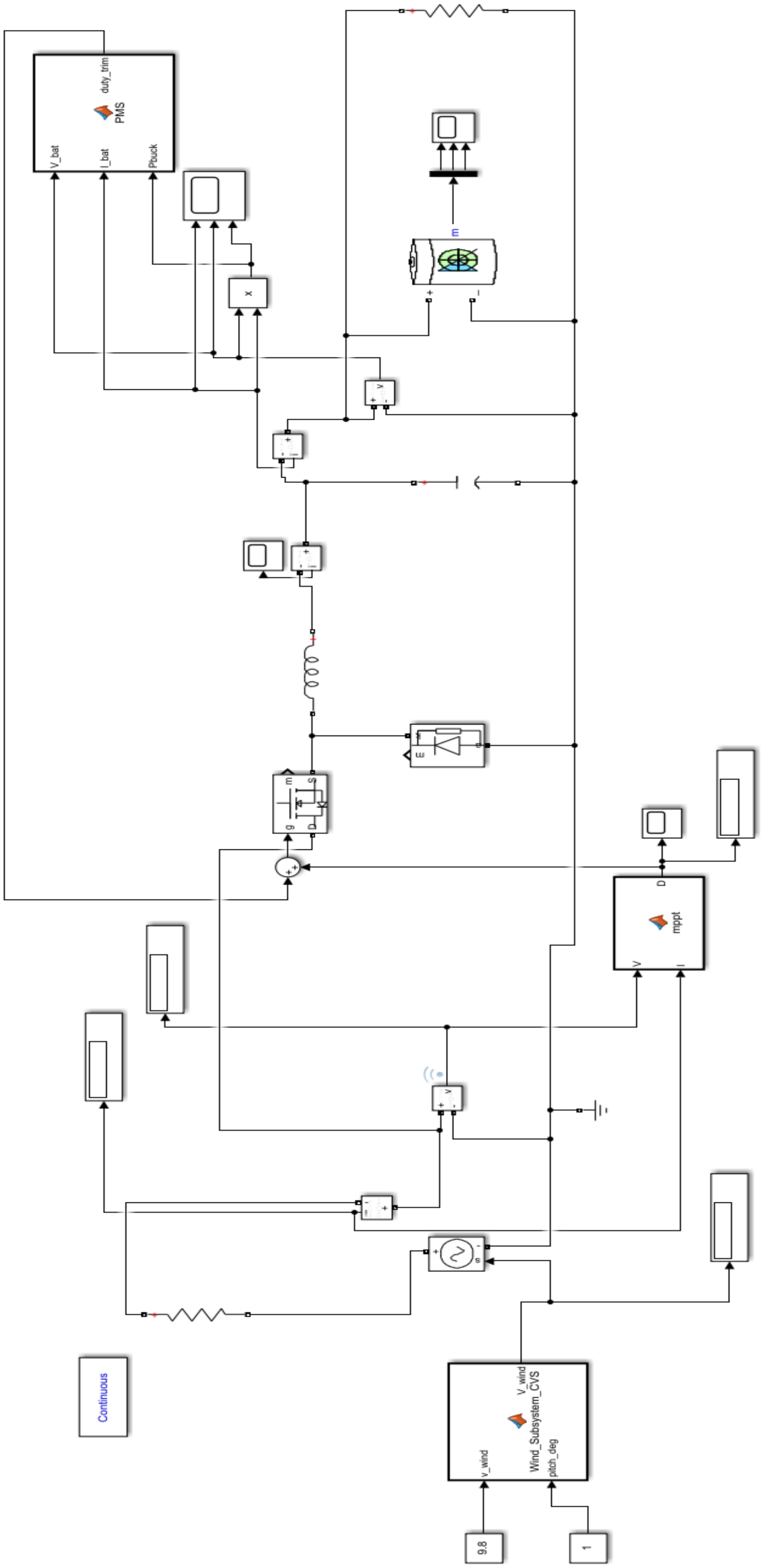

Figure 2: Simulink Model of the Wind Energy Harvesting System

3. RESULTS AND DISCUSSION

The performance of the proposed wind energy harvesting system was evaluated using MATLAB/Simulink simulations based on one-year measured wind speed data. The results are presented in terms of DC-DC converter output, power management system (PMS) output, load power, and the corresponding energy and efficiency profiles across the twelve months.

The DC-DC converter output Figure 3 exhibits clear seasonal variation, reflecting the dependence of harvested power on wind speed. In January, the system produces a moderate average output of 21.846 mW, which increases significantly in February to 31.909 mW and reaches a peak in March to 38.022 mW, with maximum values of 156.950 mW. This indicates that March corresponds to the period of highest wind energy availability. However, a noticeable decline is observed in April to 17.365 mW and Mayto 14.520 mW, coinciding with reduced wind conditions. A slight recovery occurs in June to 15.500 mW, followed by a significant increase in July to 27.170 mW and August to 38.489 mW, indicating another period of improved wind activity. Thereafter, the output decreases progressively from September to 21.803 mW to October-December approximately 14.860-14.455 mW, representing the lowest wind energy periods.

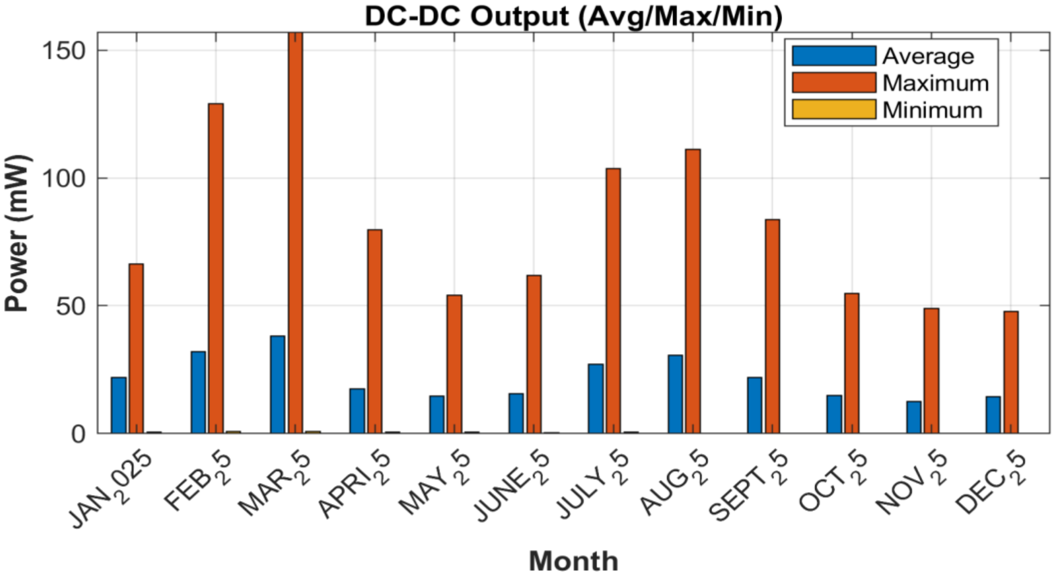

Figure 3: DC-DC Output of the Wind Energy Harvester

The PMS output Figure 4 follows a similar trend but remains consistently lower than the DC-DC output due to conversion and control losses within the power conditioning circuitry. For instance, in March, the PMS delivers an average of 33.581 mW compared to 38.022 mW at the converter stage, while in low performing months such as November, the output drops to 11.088 mW. The relatively small difference between the DC-DC and PMS outputs indicates that the PMS operates with high efficiency in regulating and transferring energy.

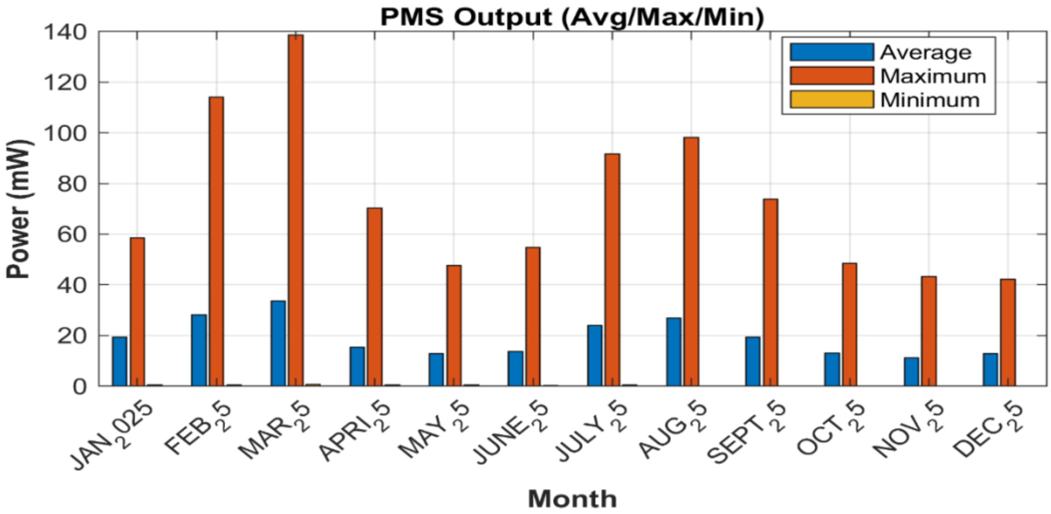

Figure 4: PMS Output of the Wind Energy Harvester

The load power profile Figure 5 further reflects the cumulative system losses, with values slightly lower than the PMS output. In peak months such as March, the load receives 31.902 mW on average, while in low wind periods such as October and November, the load power decreases to 12.468 and 10.534 mW. Despite these reductions, the system maintains continuous power delivery, demonstrating the effectiveness of the PMS in managing energy under varying input conditions.

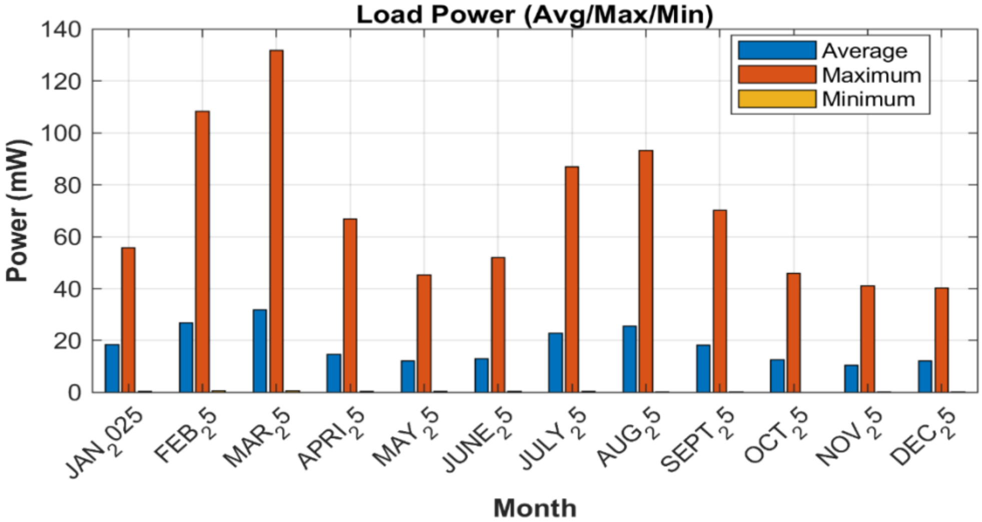

Figure 5: Load Power Output of the Wind Energy Harvester

The energy and efficiency analysis Figure 6 provides additional insight into system performance. The daily harvested energy varies significantly across the year, ranging from approximately 0.25 Wh/day in low-wind months October-November to about 0.766 Wh/day in March, with secondary peaks observed in February, July, and August. In contrast, the overall system efficiency remains relatively stable at approximately 16.47% throughout the year, with only minor fluctuations. This stability suggests that variations in output energy are primarily driven by changes in wind resource availability rather than inefficiencies in the system design.

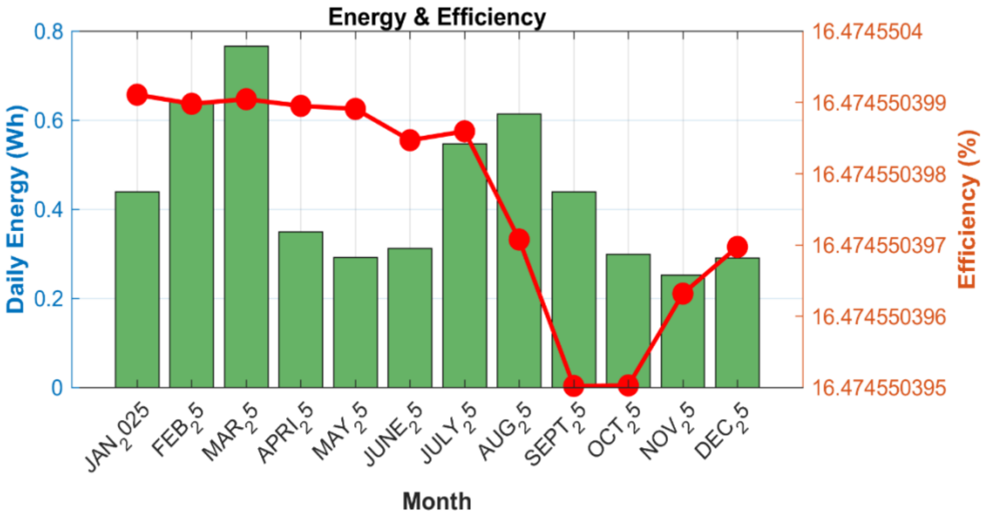

Figure 6: Daily Energy and Efficiency of the Wind Energy Harvester

Overall, the results demonstrate that the proposed wind energy harvesting system exhibits strong sensitivity to seasonal wind variations, with peak performance occurring in February and March, and minimum performance observed in May, November, and December. Despite these fluctuations, the PMS ensures stable system operation and effective energy regulation, confirming its suitability for low-speed wind energy harvesting applications, particularly for powering wireless sensor nodes, IoTs devices, and low-power electronic systems.

4. CONCLUSION

This study presents the design, modeling, and performance evaluation of a wind energy harvesting system based on real-time wind data collected over a full annual cycle. The system integrates aerodynamic energy capture, electrical conversion, MPPT control, and a power management system to ensure efficient energy extraction and delivery under variable wind conditions.

The results demonstrate that the harvested power is strongly influenced by seasonal wind variations, with maximum output observed in March and relatively lower performance during the late year months. Despite these fluctuations, the PMS consistently maintains stable power delivery to the load, effectively mitigating the impact of intermittency. The close alignment between DC-DC output, PMS output, and load power further confirms the efficiency of the energy conversion and regulation stages. Additionally, the system maintains a nearly constant efficiency of approximately 16.47%, indicating that performance variations are primarily governed by wind resource availability rather than system inefficiencies.

Importantly, the study establishes that even under low-speed wind conditions typical of the study location, meaningful electrical power in the milliwatt range can be harvested and utilized for low-power applications such as wireless sensor nodes. The integration of real-world data with a robust modeling framework enhances the reliability and practical relevance of the findings.

The proposed wind energy harvesting system demonstrates strong potential as a sustainable and reliable power solution for autonomous and remote sensing applications. Future work may focus on hybridizing the system with complementary energy sources such as solar, radio-frequency harvesting to further improve energy availability and system uptime under highly variable environmental conditions.

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