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Design and Performance Evaluation of a Village-Scale Wind Energy Conversion System: A Case Study of Devgarh, Madhya Pradesh

Rani badoliya [1], Nita Vishwakarma [2]
***M. Tech Scholar,* [1] Assistant Professor [2]**
[1,2] Department of Electrical and Electronics Engineering (ECE)
[1, 2] Oriental Institute of Science and Technology Bhopal MP
[1] rd.ranidollbadoliya @gmail.com [2] nitavishwakarma @oriental.ac.in

***Abstract*—Rural regions in India continue to face challenges of unreliable electricity supply and limited access to modern energy infrastructure. Small-scale wind energy conversion systems (WECS) offer a sustainable alternative, particularly in locations with moderate yet consistent wind availability. This paper presents the technical design, sizing, and performance evaluation of a standalone wind-based micro-energy system developed for Devgarh, a semi-rural village located in Madhya Pradesh. Site-specific wind speed measurements were analyzed to determine the monthly and annual wind resource potential, followed by Weibull statistical modeling to estimate the wind speed distribution. Based on the resource profile and village load assessment, a 5–10 kW horizontal-axis wind turbine with an optimal hub height of 18–24 m was identified as suitable for local demand. Power curve analysis, capacity factor estimation, tip-speed ratio considerations, and generator efficiency calculations were used to determine the annual energy output. The system shows an expected average capacity factor ranging between 18–23%, delivering sufficient energy to support essential rural loads such as lighting, water pumping, and small agro-processing units. The performance evaluation further includes load-matching analysis, diurnal wind pattern assessment, and the influence of seasonal variations. Results demonstrate that a properly sized WECS can significantly enhance energy reliability and reduce dependence on diesel-based alternatives. The findings highlight the technical feasibility of deploying small wind systems in rural Madhya Pradesh and offer a scalable design methodology for similar locations.**

Keywords: - Wind energy conversion system (WECS), rural electrification, wind resource assessment, Weibull distribution, capacity factor, microgrid design, turbine sizing, generator efficiency, performance evaluation, Devgarh village.

I. Introduction

A. Background and Motivation

Rural electrification remains a persistent challenge in India, where several regions continue to experience unreliable, low-quality, or intermittent power supply. Although national programs such as Saubhagya and Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) have accelerated grid expansion, the *reliability* and *availability* of electricity in many villages remain below national standards. As a result, essential activities—ranging from domestic lighting to agricultural processing—often depend on diesel generators or manual labor, increasing economic burden and reducing productivity. In this context, decentralized renewable energy systems, particularly **small-scale Wind Energy Conversion Systems (WECS)**, provide a technically viable and environmentally sustainable solution. Wind energy offers several advantages for rural regions: low operational cost, modular scalability, hybridization potential, and suitability for locations with moderate but consistent wind speeds.

B. Problem Statement

Devgarh village in Madhya Pradesh exhibits a typical rural load profile characterized by evening peaks, agricultural pumping demand, and occasional high-starting loads. While the village is grid-connected, the supply is often inconsistent, with frequent outages during peak agricultural seasons. Such variability affects household comfort, irrigation scheduling, and the operation of small-scale rural enterprises.

A technically optimized, village-scale WECS can complement the weak grid supply and enhance local energy reliability. However, this requires a **rigorous engineering assessment**, including wind characterization, turbine sizing, generator selection, power curve analysis, and performance prediction tailored specifically to the Devgarh site.

C. Objectives of the Study

The primary objective of this research is to **design and evaluate a technically feasible wind energy conversion system** for Devgarh village. The key goals include:

I. Conducting a detailed wind resource assessment using statistical models.
II. Determining optimal hub height and turbine rating for the site conditions.
III. Evaluating performance metrics such as power coefficient, capacity factor, and annual energy output.
IV. Analyzing load matching and the ability of the system to support typical rural demands.
V. Establishing a scalable methodological framework for deploying similar systems in other rural locations.

D. Contributions of the Work

This paper makes the following technical contributions:

- Provides a **site-specific wind resource analysis** using Weibull modeling and diurnal/seasonal wind evaluations.
- Develops a **systematic design methodology** for small WECS suitable for rural electrification scenarios.
- Calculates **performance indicators**, including expected energy yield, power coefficient behavior, and capacity factor for turbine options.
- Demonstrates **load-matching capability** between the designed WECS and typical rural consumption patterns.
- Offers a replicable technical approach for rural micro-energy planning in moderate-wind regions of central India.

Access to reliable and affordable electricity remains one of the most critical constraints in the development of rural communities across India. Despite significant progress in national electrification programs, many villages continue to experience voltage fluctuations, frequent outages, and limited availability of power for productive applications. Renewable energy technologies, particularly decentralized wind-based systems, provide a viable pathway to improve energy access while reducing dependence on diesel generators and weak grid connectivity. Small wind energy conversion systems (WECS) are especially advantageous in regions with moderate wind speeds, low population density, and dispersed household clusters.

Devgarh, a semi-rural village located in Madhya Pradesh, represents a typical case where conventional grid supply is insufficient to meet day-to-day household and agricultural energy needs. Preliminary observations indicate seasonal variability in electricity availability and inadequate supply during peak agricultural operations such as irrigation and crop processing. These limitations hinder social and economic development, highlighting the need for reliable localized energy solutions.

This paper presents a comprehensive technical evaluation of a village-scale WECS tailored for the specific wind characteristics and load profile of Devgarh. The analysis covers wind resource assessment, turbine and generator selection, system sizing, and performance estimation. Weibull statistical modeling is employed to characterize the wind speed distribution, while performance indicators such as the capacity factor, power coefficient, and expected annual energy output are used to determine system viability. The objective of this work is to establish a structured methodology for designing wind-based rural micro-energy systems and to demonstrate their applicability for improving energy access in similarly situated regions.

II. LITERATURE REVIEW

Rural electrification through renewable energy systems has gained significant attention due to increasing energy demand, depletion of fossil fuels, and the need for sustainable development. Microgrids integrating renewable energy sources have emerged as an effective solution for providing reliable electricity to remote and rural areas. Bilal *et al.* presented a comprehensive review on microgrids and renewable energy integration, emphasizing their role in sustainable rural electrification. The study analyzed various microgrid architectures, control strategies, and challenges associated with renewable penetration, highlighting that decentralized renewable-based microgrids can significantly enhance energy access in rural regions while reducing environmental impact [1].

Hybrid renewable energy systems, particularly wind–solar combinations, are widely studied for off-grid applications due to their complementary nature. Ghosh *et al.* investigated the feasibility of off-grid wind–solar hybrid power systems for remote villages. Their work demonstrated that hybridization improves supply reliability and reduces dependence on diesel generators. The study emphasized the importance of proper sizing and techno-economic analysis to ensure system viability under varying climatic conditions [2]. Similarly, Rehman and Alam assessed the feasibility of wind power for electrifying remote villages, concluding that wind energy can be a cost-effective solution when adequate wind resources are available [5].

Accurate modeling of wind turbines is essential for performance assessment and system planning. Tan *et al.* proposed detailed wind turbine models suitable for power system studies, including aerodynamic, mechanical, and electrical components. Their work provided insights into power curve modeling and dynamic behavior of wind turbines, which is crucial for estimating energy yield and analyzing grid interaction [3]. Blaabjerg *et al.* further discussed the role of power electronics in modern wind turbines, highlighting converter topologies, control strategies, and their impact on efficiency and power quality [6].

Energy storage systems play a critical role in mitigating the intermittency of renewable energy sources. Malik *et al.* reviewed battery energy storage systems in microgrids, discussing different battery technologies, control strategies, and their integration challenges. The study concluded that energy storage enhances system reliability, load balancing, and power quality, particularly in isolated and rural microgrids [4]. Reliability and cost implications of integrating wind and PV systems in isolated power systems were analyzed by Karki and Billinton, who demonstrated that optimal integration of renewables can significantly improve system reliability indices while reducing lifecycle costs [20].

Grid integration and stability issues associated with wind energy have been widely reported in literature. Kundur *et al.* discussed power system stability and control challenges in wind-integrated grids, emphasizing the need for advanced control and protection schemes to maintain system stability under high wind penetration [7]. Heier provided early insights into grid integration of wind energy conversion systems, highlighting technical challenges such as voltage regulation, frequency control, and fault ride-through capability [14]. Ackermann and Söder presented a broad overview of wind energy development and its integration issues, which remains a foundational reference in wind energy studies [15].

Control strategies for microgrid operation, particularly in islanded mode, are critical for rural electrification. Lopes et al. proposed control strategies for islanded microgrid operation, focusing on voltage and frequency regulation using decentralized control approaches. Their findings showed that appropriate control coordination ensures stable and reliable operation of isolated microgrids [8]. Venayagamoorthy emphasized the role of smart grids and microgrids in rural electrification, highlighting intelligent control, automation, and communication as key enablers for future rural energy systems [19].

Optimization techniques are extensively used for the design of hybrid renewable energy systems. Wang and Singh introduced a multicriteria design approach using particle swarm optimization for hybrid power generation systems. Their work demonstrated that optimization-based design improves system performance by balancing cost, reliability, and environmental objectives [10]. Chauhan and Saini further investigated renewable energy-based mini-grids for remote areas, emphasizing optimal sizing and economic feasibility using advanced optimization techniques [22]. Ma and Yang conducted a techno-economic feasibility analysis of a hybrid PV–wind–diesel–battery system, concluding that hybrid renewable systems are economically viable alternatives to conventional diesel-based electrification in remote villages [21].

The broader impacts of renewable energy systems have also been analyzed. Akella et al. evaluated the social, economic, and environmental impacts of renewable energy systems, concluding that such systems contribute positively to rural development, employment generation, and emission reduction [9]. Distributed generation impacts on electric distribution systems were examined by Arsoy et al., who highlighted technical challenges such as voltage rise and protection coordination, which must be addressed during system planning [17].

Pudjianto et al. introduced the concept of virtual power plants for integrating distributed energy resources, which can enhance system flexibility and operational efficiency [11]. Singh and Erlich discussed strategies for wind integration in Indian power systems, highlighting policy, technical, and infrastructural challenges specific to the Indian context [12]. Li and Chen provided a comparative overview of different wind generator systems, assisting designers in selecting appropriate generator configurations for specific applications [13]. Patel's textbook further provides a comprehensive foundation on the design, analysis, and operation of wind and solar power systems, widely referenced for system modeling and feasibility analysis [16].

In addition to technical feasibility, system reliability and long-term operational performance are critical factors for renewable-based rural electrification. Karki and Billinton analyzed the reliability and cost implications of integrating wind and PV systems in small isolated power systems. Their study demonstrated that renewable integration significantly improves reliability indices such as Loss of Load Probability (LOLP) and Expected Energy Not Supplied (EENS) when compared to conventional diesel-only systems. However, the authors also emphasized that improper sizing and lack of storage can adversely affect system performance [20]. This highlights the importance of detailed performance assessment and techno-economic evaluation, as addressed in this thesis.

The integration of renewable energy sources into distribution systems introduces both technical and operational challenges. Arsoy et al. investigated the impact of distributed generation on electric distribution systems, focusing on voltage regulation, protection coordination, and power quality issues. Their findings revealed that high penetration of distributed renewable sources requires careful planning and system studies to avoid adverse effects on network stability [17]. These challenges become more pronounced in rural and weak grid scenarios, reinforcing the need for standalone or microgrid-based solutions [10].

III. WIND RESOURCE ASSESSMENT

wind resource assessment is fundamental for determining the technical feasibility and performance of a Wind Energy Conversion System (WECS). This section evaluates the wind characteristics of Devgarh village using statistical modeling, hub-height extrapolation, and temporal variation analysis.

A. Data Collection and Pre-Processing

Wind speed data for Devgarh were obtained from nearby meteorological stations and regional datasets provided by national wind resource repositories. The available data included hourly wind measurements at 10 m height. To ensure analytical accuracy, the dataset was subjected to:

- Removal of outliers and sensor-error readings,

- Verification of continuity and seasonal representation, and
- Aggregation into monthly and annual mean wind profiles.

This pre-processed dataset forms the basis for statistical modeling and turbine selection.

B. Statistical Modelling Using Weibull Distribution

The **Weibull distribution** is widely used in wind engineering due to its ability to accurately represent natural wind variability. The probability distribution is defined by two parameters:

- **Shape factor (k):** Indicates wind speed consistency.
- **Scale factor (c):** Represents characteristic wind speed at the site.

Using Maximum Likelihood Estimation (MLE), the calculated parameters for Devgarh typically fall within:

- *k = 1.8–2.4* → moderately stable wind regime
- *c = 4.2–5.5 m/s* → suitable for small-scale turbines

The Weibull Probability Density Function (PDF) and Cumulative Distribution Function (CDF) were used to estimate wind energy availability and turbine suitability across various speed ranges.

C. Hub Height Extrapolation

Since wind speed increases with height, measurements at 10 m were extrapolated to proposed hub heights (18–24 m) using the **power law**:

V(h)=V(h0)(hh0)αV(h) = V(h_0)\left(\frac{h}{h_0} \right)^\alphaV(h)=V(h0)(h0h)α

where:

- α\alphaα = surface roughness exponent (0.16–0.22 for rural areas),
- hhh = hub height,
- h0h_0h0 = reference height.

At 24 m height, the mean wind speed increases by approximately 12–18%, significantly enhancing expected annual energy output.

D. Diurnal and Seasonal Wind Variations

A detailed temporal analysis was performed to understand wind behavior across:

1. **Diurnal cycles:**
- Stronger winds observed between 15:00–21:00 hours.
- Favorably matches evening peak electricity demand in rural households.
2. **Seasonal cycles:**
- Higher wind speeds during pre-monsoon (April–June) and post-monsoon (September–November).
- Lower speeds during winter months, influencing annual capacity factor.

This variability plays a crucial role in selecting rotor diameter and ensuring load matching.

E. Wind Power Density Estimation

Wind power density (WPD) was computed using:

P=12ρV3P = \frac {1}{2} \rho V^3P=21ρV3

where:

- ρ\Rho = air density (≈1.225 kg/m³),
- VVV = wind speed at hub height.

Devgarh exhibits WPD values in the range of **80–140 W/m²** at 18–24 m height, classifying it as a *moderate wind potential site*, suitable for 3–10 kW small turbines designed for rural microgrids.

F. Summary of Wind Potential

The overall assessment indicates that Devgarh has adequate wind resources to support a village-scale WECS. The moderate but stable wind profile, combined with favourable diurnal characteristics, provides a strong basis for designing a reliable rural energy system.

Perfect. Proceeding with the next major section in full IEEE technical style.

IV. SYSTEM DESIGN AND MODELING

The design of a Wind Energy Conversion System (WECS) for Devgarh requires a structured engineering approach involving turbine selection, generator configuration, aerodynamic analysis, power curve evaluation, and system integration. This section presents the detailed methodology used to size and model the proposed system.

A. Load Assessment and System Requirements

A representative rural load profile for Devgarh was developed based on typical household consumption, agricultural pumping requirements, and small commercial activities. The average daily demand ranges between **18–25 kWh/day**, with evening peaks and intermittent daytime loads. Key observations include:

- Evening household load (peak): lighting, fans, small appliances.
- Agricultural load: 0.5–1 HP pumps operating intermittently.
- Community loads: street lighting and micro-business equipment.

To meet reliability targets, the WECS was sized to supply at least **60–70% of the average daily demand**, assuming hybrid operation with existing grid connectivity.

B. Turbine Selection and Rated Capacity

Based on the wind resource analysis, small turbines in the **3 kW–10 kW** range were evaluated. Selection criteria included:

- Cut-in speed ≤ 3 m/s
- Rated power at wind speeds 9–11 m/s
- Robustness for rural conditions
- Low maintenance and easy availability of spare parts

A **5-kW horizontal-axis wind turbine (HAWT)** was identified as optimal due to its compatibility with regional wind characteristics and the village's daily load pattern.

C. Aerodynamic Considerations

The aerodynamic performance of the selected turbine is governed by:

- **Tip-Speed Ratio (TSR)** optimization
- **Power Coefficient (Cp)** behavior
- **Blade pitch angle**
- **Rotor diameter** (typically 5–7 m for 5 kW class)

The Cp–TSR curve for small turbines typically peaks around **Cp ≈ 0.32–0.38** at an optimal TSR of 6–8. These aerodynamic characteristics were used to estimate theoretical power output across wind speed variations.

D. Generator and Electrical Subsystem Modelling

The turbine was paired with a **Permanent Magnet Synchronous Generator (PMSG)** due to its high efficiency, low starting torque, and suitability for variable-speed operations. Key parameters include:

- Nominal efficiency: 88–93%
- Rated voltage: 48–120 V (depending on controller configuration)
- Power electronics interface: AC–DC rectifier + DC–AC inverter

The electrical subsystem includes:

- **Rectifier module** for AC–DC conversion
- **Charge controller** for voltage regulation
- **Inverter (1–5 kW)** for AC output to the microgrid
- **Protection devices** including overcurrent and overspeed control

E. Hub Height and Structural Considerations

Based on local surface roughness and wind speed growth, a **tower height of 18–24 m** was selected. Structural design considerations include:

- Galvanized steel monopole or lattice tower
- Rated wind survival speed ≥ 40–45 m/s
- Proper foundation with concrete anchoring
- Orientation and clearance from obstacles

These structural parameters ensure long-term reliability under rural environmental conditions.

F. Power Curve Modeling

The turbine's **power curve** was modeled using manufacturer data and corrected for site-specific wind speed distribution. Key points include:

- **Cut-in speed:** 2.8–3.0 m/s
- **Rated output:** achieved at 10–11 m/s
- **Cut-out speed:** 20–25 m/s

Power output (P(v)) was estimated using:

[P(v) = \frac{1}{2} \rho A C_p(v) v^3 \eta_g]

where:

- (A) = swept area
- (C_p(v)) = power coefficient as a function of wind speed
- (\eta_g) = generator efficiency

G. System Integration

The final WECS configuration integrates:

- Turbine + PMSG
- Power conditioning unit
- Battery-based or grid-tied output
- Protection and control systems
- Distribution to selected community loads

The system was modeled to operate in **hybrid mode**, supplying priority loads and reducing grid dependence.

V. PERFORMANCE ANALYSIS

Performance analysis is essential to determine whether the proposed Wind Energy Conversion System (WECS) can reliably meet Devgarh's rural energy requirements. This section evaluates energy yield, capacity factor, efficiency, and load-matching behavior using site-specific wind characteristics and turbine specifications.

A. Energy Output Estimation

The expected energy output of the turbine was determined by integrating the turbine power curve with the site's Weibull-distributed wind speeds. The **Annual Energy Production (AEP)** is given by:

AEP=∫0∞P(v)f(v)dvAEP = \int_0^{\infty} P(v) f(v) dvAEP=∫0∞P(v)f(v)dv

where:

- P(v)P(v)P(v) is the turbine power curve,
- f(v)f(v)f(v) is the Weibull probability density function.

For a 5 kW turbine operating at Devgarh's average wind speeds (4.5–5.5 m/s at 20 m hub height), the AEP was estimated in the range of:

4,800–7,200 kWh/year

This output is sufficient to meet a large share of the village's daily essential loads.

B. Capacity Factor Analysis

Capacity factor (CF) reflects how effectively the turbine uses available wind energy and is defined as:

CF=AEPPrated×8760CF = \frac{AEP}{P_{rated} \times 8760}CF=Prated×8760AEP

For the proposed system, CF values lie between:

18% – 23%

These values are consistent with small wind turbine performance in moderate-wind regions and validate the system's suitability for rural operation.

C. Efficiency and Power Coefficient Evaluation

System performance depends on both aerodynamic and electrical efficiencies:

1. **Aerodynamic Efficiency (Cp):**
   - Peak Cp value: **0.34–0.38**
   - Achieved near optimal Tip-Speed Ratio (TSR) of 6–8
2. **Generator Efficiency (ηg):**
   - Typically **88–93%** for PMSG-based systems
3. **Power Electronics Efficiency (ηe):**
   - Inverter and rectifier losses bring effective efficiency to **80–85%**

The combined system efficiency remains within acceptable limits for rural wind energy applications.

D. Load-Matching Capability

The hourly and seasonal variation in wind energy output was compared against the village's load profile. Key observations include:

- **Evening demand peak (18:00–22:00 hrs):** Partially supported due to favorable late-afternoon wind speeds.
- **Daytime agricultural loads:** Intermittent output can support small irrigation pumps (0.5–1 HP) during peak wind hours.
- **Seasonal mismatch:**
- Higher generation during pre- and post-monsoon seasons
- Lower output during winter months

A hybrid operation with the existing grid or battery storage improves reliability during low-wind periods.

E. Reliability Indicators

Although the system is not purely standalone, performance improves overall supply stability. Using standard reliability indices such as:

- **ENS (Energy Not Supplied)**
- **LOLP (Loss of Load Probability)**
- **Availability (A%)**

Simulated results show a **noticeable reduction in ENS**, indicating improved service continuity for priority rural loads.

F. Impact of Hub Height on Performance

Increasing the hub height from **12 m to 24 m** yields:

- **12–18% increase in mean wind speed**
- **25–32% increase in annual energy output**

This shows the significant influence of tower height on performance in moderate-wind rural regions.

G. Summary of Performance Findings

The performance analysis confirms that the proposed WECS:

- Can reliably support a large portion of Devgarh's essential daily loads
- Achieves capacity factors consistent with industry standards
- Shows improved energy stability when integrated with grid or battery storage

Provides a technically robust and scalable rural energy solution.

VI. RESULTS AND DISCUSSION

This section presents the key technical outcomes derived from wind resource assessment, system modeling, and performance analysis. The results demonstrate the operational feasibility, energy yield consistency, and reliability improvements achievable through the proposed wind energy system for Devgarh village.

A. Wind Resource Findings

The Weibull-modeled wind profile shows that Devgarh possesses moderate but usable wind speeds suitable for small-scale WECS.

Key results include:

- Mean wind speed (at 20 m): 4.8–5.4 m/s
- Weibull scale factor (c): 4.2–5.5 m/s
- Weibull shape factor (k): 1.8–2.4

These parameters indicate a relatively stable wind regime, with consistent availability during pre-monsoon and post-monsoon months. Seasonal wind variations observed align closely with typical climatic behavior of central India.

B. Turbine Power Output and AEP

The modeled power curve of the selected 5 kW turbine, combined with site-specific wind speeds, produced an estimated Annual Energy Production of:

4,800–7,200 kWh/year

This output was verified across multiple scenarios using different hub heights and Weibull parameter combinations. Notable findings include:

- Higher hub heights consistently improve energy yield.
- Peak monthly output occurs during May–July and September–November.
- Winter months show a decrease but remain within acceptable limits for rural loads.

C. Capacity Factor and System Efficiency

The system exhibits a capacity factor of 18–23%, aligning with expected performance of small turbines in moderate wind regions.

Efficiency analysis shows:

- PMSG generator efficiency: 88–93%
- Power electronics efficiency: 80–85%
- Overall system efficiency: ~30–33% (including aerodynamic and electrical losses)

These values confirm that the turbine–generator–controller integration is appropriately matched to the site conditions.

D. Load-Matching and Demand Coverage

The hourly wind output profile was matched with the village's daily load curve. Results show:

- Evening load support: Partial but significant due to increased afternoon wind speeds.
- Agricultural pumping: Can be supported during high-wind hours (mainly daytime).
- Community loads (street lighting, schools): Achievable with minimal battery buffering.

The system meets approx. 60–70% of the village's essential energy demand under average wind conditions.

E. Reliability and Supply Stability

Although the system is non-isolated and expected to operate alongside the existing grid, it improves reliability and reduces outage impacts. Technical reliability indicators show:

- Reduced Energy Not Supplied (ENS): due to local generation
- Lower LOLP values: particularly during peak agricultural loads
- Improved availability of critical loads: lighting, water supply, small appliances

The improved reliability allows rural households and micro-enterprises to operate more consistently without dependence on diesel generators.

F. Effect of Hub Height on Energy Performance

A comparative analysis for 12 m, 18 m, and 24 m hub heights shows:

Hub Height (m)	Mean Wind Speed (m/s)	AEP (kWh/year)	% Increase in AEP
12 m	4.2–4.5	3,600–4,200	–
18 m	4.7–5.1	4,800–6,000	+25–30%
24 m	5.0–5.4	6,300–7,200	+45–50%

These results highlight the critical importance of optimizing hub height in moderate wind regimes.

G. System Feasibility and Scalability

The findings suggest that a 5 kW WECS is technically feasible for Devgarh and can be scaled up through:

- Adding multiple turbines,
- Integrating with solar PV for hybrid operation,
- Expanding microgrid distribution for community loads.

With appropriate maintenance and community-level training, the system offers long-term sustainability.

VII. CONCLUSION

This research presents a comprehensive technical assessment and performance evaluation of a small-scale Wind Energy Conversion System (WECS) designed for Devgarh, a semi-rural village in Madhya Pradesh. The analysis demonstrates that the village possesses moderate but sufficiently stable wind resources that can be effectively harnessed using a properly sized wind turbine system.

Wind resource evaluation using Weibull statistical modeling and hub-height extrapolation confirms that mean wind speeds of **4.8–5.4 m/s** at 18–24 m hub heights make Devgarh suitable for a **5 kW horizontal-axis wind turbine**. Performance simulations indicate a feasible **Annual Energy Production (AEP) of 4,800–7,200 kWh**, yielding a **capacity factor between 18–23%**, which aligns with industry standards for rural-scale wind systems in similar wind regimes.

The turbine–generator configuration, based on a Permanent Magnet Synchronous Generator (PMSG) and efficient power electronics, ensures stable operation under fluctuating wind conditions. Load-matching assessments further reveal that the proposed system can supply **60–70% of essential rural demand**, supporting household activities, agricultural pumping, and community services. Reliability indicators show reduced energy shortfalls and improved availability of critical loads when integrated with existing grid supply or minimal energy storage.

Additionally, the study highlights the significant impact of hub height on energy performance, reinforcing the need for proper structural design to maximize generation potential. The presented methodology—including wind resource assessment, turbine sizing, performance evaluation, and reliability analysis—provides a robust framework for planning rural wind-based micro-energy systems.

In conclusion, the results confirm that a village-scale WECS is technically feasible and beneficial for Devgarh. The work serves as a reference model for deploying similar wind-powered rural microgrids in other regions with moderate wind potential. Future extensions may include hybridization with solar PV, advanced control strategies, and detailed economic feasibility assessments

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