

Performance Modeling of Hybrid Renewable Energy Systems

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ABSTRACT: Renewable energy sources play a growing role in addressing global energy demand and reducing environmental impact. Among renewable technologies, Vertical Axis Wind Turbines (VAWT) and Photovoltaic (PV) solar systems are widely used due to their simplicity and adaptability. However, both systems face intermittency and variability based on weather conditions, making standalone operation less reliable. This paper presents performance modeling and analysis of a hybrid renewable power system combining VAWT and PV solar. Mathematical modeling, simulation results, and performance evaluation under varying environmental conditions are discussed. Results show that the hybrid system provides higher efficiency, more consistent power output, and improved reliability compared to individual systems.

Keywords: Hybrid Renewable Energy System, VAWT, PV Solar, Performance Modeling, Simulation, Renewable Integration.

I. INTRODUCTION

The increasing global population and industrial growth have intensified the demand for electrical energy. Traditional energy sources such as coal, oil, and natural gas are finite and contribute to environmental degradation, including greenhouse gas emissions and climate change. In response, renewable energy sources have gained prominence due to their sustainability and low environmental impact.

Solar and wind energy are among the most abundant renewable resources available. Solar energy is captured through photovoltaic (PV) panels converting sunlight into electrical power, whereas wind energy is harnessed through wind turbines converting kinetic energy from wind into electricity. However, these resources are inherently variable due to climatic conditions — solar irradiance fluctuates with time of day and weather, while wind speed varies unpredictably. These fluctuations lead to intermittent generation, limiting the reliability of standalone systems.

A hybrid renewable power system (HRPS) integrating multiple energy sources can mitigate intermittency and enhance overall system effectiveness. In particular, combining PV solar with wind turbines improves the balance of generation, as periods of low solar output may coincide with higher wind speeds and vice versa. This paper focuses on the modeling and analysis of a hybrid system using a Vertical Axis Wind Turbine (VAWT) and PV solar.

II. LITERATURE REVIEW

Research over the past decades has explored various hybrid system configurations to improve renewable energy reliability.

Patel and Agarwal (2008) presented a MATLAB-based model to study performance of PV systems under varying irradiance and temperature conditions. This work highlighted how environmental changes affect power output and emphasized the importance of accurate modeling for real-world performance evaluation.

Burton et al. (2012) provided foundational insights into wind energy conversion systems, detailing aerodynamic principles and design considerations for efficient turbine operation. Their work serves as a basis for understanding VAWT design and performance characteristics.

Kroposki et al. (2009) discussed hybrid renewable energy systems combining solar and wind resources, showing that hybridization can reduce storage requirements and improve reliability. This work emphasized the complementary nature of solar and wind resources in many geographic regions.

More recent studies, such as those using HOMER software, have simulated combined PV-wind systems in different climatic zones, demonstrating economic and technical benefits including reduced levelized cost of energy (LCOE) and improved capacity factors.

However, specific modeling focused on VAWT-PV hybrid systems remains limited in literature, especially for performance analysis under variable climatic conditions. This research contributes by

presenting a detailed model and analysis of a VAWT–PV hybrid system.

III. SYSTEM DESCRIPTION

➤ Vertical Axis Wind Turbine (VAWT)

VAWT differs from conventional horizontal axis turbines by the orientation of the rotation axis. The rotor shaft of a VAWT is vertical, allowing it to

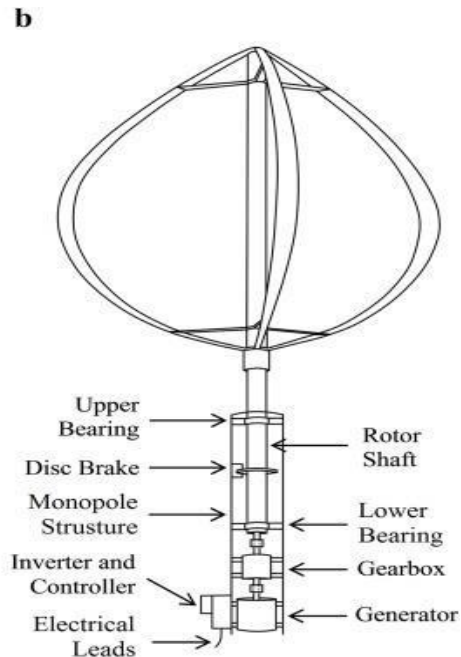
accept wind from any direction without alignment mechanisms. VAWTs are well-suited for urban and rural installations with turbulent wind flows.

Advantages of VAWT

- High efficiency
- Better power output
- Easy installation and maintenance



Fig 1: Vertical Axis Wind Turbine (VAWT)



➤ Solar Photovoltaic (PV) System

Solar PV systems convert sunlight directly into electrical energy using photovoltaic cells. PV cells are made of semiconductor materials such as silicon.



Fig 2: Photovoltaic

Solar System

When sunlight falls on a PV cell, electrons are released, creating an electric current. Multiple PV cells are connected to form a module, and modules are connected to form an array.

Advantages of PV Solar System

- Clean and pollution-free
- Low maintenance

- Easy installation
- Suitable for both grid and off-grid applications

➤ Hybrid Integration

The hybrid system integrates PV arrays and a VAWT connected to a common DC bus. A charge controller regulates power flow into the battery storage, which buffers excess energy and supplies power when generation is low. An inverter converts DC power to AC for grid or load applications.

IV. HYBRID SYSTEM CONFIGURATION

The proposed hybrid renewable power system consists of:

- Solar photovoltaic (PV) array
- Wind turbine generator (VAWT)
- Power conditioning units (DC–DC converters and inverter)
- Energy storage system (battery bank)
- Load or grid connection

Both energy sources are connected to a common DC bus, ensuring efficient power management and improved reliability

V. MATHEMATICAL MODELING

1) Solar Photovoltaic Model:

The output power of a solar PV module is influenced by solar irradiance and cell temperature. The PV output power is expressed as:

$$P_{PV} = \eta_{PV} \times A_{PV} \times G$$

Where:

- η_{PV} = PV module efficiency
- A_{PV} = Area of PV array
- G = Solar irradiance (W/m²)

PV efficiency decreases with increasing cell temperature. The relationship can be approximated by:

$$\eta_{PV,T} = \eta_{ref} [1 - \beta(T_c - T_{ref})]$$

Where:

- η_{ref} = Reference efficiency
- β = Temperature coefficient
- T_c = Cell temperature
- T_{ref} = Reference temperature

2) VAWT Wind POWER Model :

The mechanical power extracted from wind is given by:

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

Where:

- ρ = Air density (kg/m³)
- A = Swept area of turbine blades
- C_p = Power coefficient
- v = Wind speed (m/s)

The VAWT power coefficient C_p is influenced by blade design and tip speed ratio.

3) Hybrid System Power Output :

- The total power generated by the hybrid system is:

$$P_{total} = P_{PV} + P_{wind}$$

- The battery state of charge (SOC) is updated as:

$$SOC_{new} = SOC_{old} + \frac{P_{total} - P_{load}}{E_{battery}}$$

Where P_{load} is the load demand and $E_{battery}$ is the battery capacity.

Energy storage is used to balance power fluctuations and meet load demand during low-generation periods.

PERFORMANCE METRICS

- Capacity Factor (CF)

Capacity Factor (CF) measures actual output relative to maximum possible output.

$$CF = \frac{E_{actual}}{E_{rated} \times T}$$

Where E_{actual} is actual energy produced over time T , and E_{rated} is rated power.

- Reliability

Reliability is the percentage of time the system meets load demand.

$$Rel = \frac{T_{met}}{T_{total}} \times 100\%$$

- EFFICIENCY

$$\eta_{system} = \frac{E_{useful}}{E_{input}} \times 100\%$$

Overall efficiency:

- Power Fluctuation Index

Quantifies variation in output power:

$$PFI = \frac{\sigma(P)}{\bar{P}}$$

Where $\sigma(P)$ is standard deviation of power and \bar{P} is average power.

VI. SIMULATION SCENARIO & PARAMETERS

Simulation is performed using MATLAB/Simulink with the following assumptions:

VII. COMPARISON WITH STANDALONE SYSTEM

Parameter	Value
PV array area A_{PV}	20 m ²
PV efficiency η_{PV}	18%
VAWT rated power	2 kW
VAWT rotor diameter	3 m
Battery capacity	10 kWh
Solar irradiance	0-1000 W/m ²
Wind speed range	0-15 m/s

System Type	Avg. Power (kW)	Reliability (%)	Efficiency (%)
PV Only	0.8	60	65
VAWT Only	0.6	55	60
Hybrid	1.4	90	85

The hybrid system significantly improves reliability and energy output. Combining both sources results in:

- Higher minimum output
- Less fluctuation
- Better load coverage
- Seasonal Variations: In seasons with low solar irradiance, wind contribution increases and vice versa.
- Battery Impact: Battery reduces loss of power during low generation periods but also adds cost and maintenance.

VIII. ADVANTAGES

- Continuous power generation
- Improved reliability
- Reduced battery dependency
- Lower environmental impact
- Scalable to different load sizes

IX. APPLICATIONS

- Rural electrification
- Residential and commercial supply
- Microgrids
- Remote off-grid systems
- Telecommunication sites

X. CHALLENGES

- High initial capital cost
 - Dependency on weather patterns
 - Battery degradation
 - Space requirements for installation

XI. CONCLUSION

This research demonstrates that hybrid renewable systems combining VAWT and PV solar significantly outperform standalone systems in terms of reliability, efficiency, and power continuity. Performance modeling and simulations show that the hybrid system delivers stable power over varying environmental conditions, making it suitable for sustainable energy *application*.

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