

Design, Fabrication, and Experimental Evaluation of a Hybrid Solar–Wind Energy System for Decentralized Power Generation

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ABSTRACT

Individual renewable energy sources tend to be intermittent, which restricts their usefulness in decentralized power use. Hybrid renewable energy systems deal with this challenge through the incorporation of supplementary energy carriers. This paper describes the design, computer-aided modeling, manufacturing, installation, and testing of a small-scale hybrid solar-wind energy unit. The machine incorporates a vertical axis wind turbine, a photo-voltage panel, a battery-based energy storage unit, and a spur gear transmission to improve the rotational speed of the generator when the wind is low. The entire system was installed successfully in a highway setting and it was tested in actual outdoor operating conditions. The experimental observations evaluate the electrical performance, battery recharge characteristics and stability in varying wind and solar conditions. The findings indicate better continuity of the energy and more stable power delivery in comparison to single wind or solar operation. The suggested system demonstrates viable potential in decentralized applications, including highway lighting and off-grid rural electrification, which provides a low-cost, modular, and scalable energy solution.

Keywords: Hybrid Renewable Energy Systems, Vertical Axis Wind Turbine, Photo-Voltage Panel, Energy Storage Unit, Decentralized Applications, Highway Lighting

INTRODUCTION

The rising need of energy in the world is attributable to the growth of populations, urbanization, and industrial development [1–4]. Traditional electricity production with fossil fuels leads to greenhouse gases, climate change, and natural resource depletion that encourages a shift toward renewable energy technologies [5–9]. Among the commonly installed types of renewable energy sources are solar and wind because of its abundance, technological maturity, and lack of environmental impact [10–12].

In spite of their benefits, individual renewable energy systems are affected by intermittency and variability. The amount of solar power can only be harnessed during daytime and is influenced by weather and wind power is subject to local wind patterns and therefore may vary erratically. These constraints lower the reliability especially when used in off-grids and decentralized systems where consistent power is important [13,14].

Hybrid renewable energy systems integrate more than one supplementary source, e.g., solar and wind, to reduce intermittency and enhance energy provision. The addition of energy storage makes power delivery even more stable, improves battery usage, and allows operation stability under unstable environmental conditions [15–17]. The proposed research is devoted to the design, CAD-based development, fabrication, installation, and experimental testing of a mini-scale hybrid solar-wind energy system. The system aimed at the decentralized applications such as highway lighting and rural electrification and proves to be a low cost, modular and scalable system of delivering continuous energy.

Literature Review

The common solution that has been considered to address the shortcomings of standalone renewable sources is the hybrid solar-wind energy system. According to studies, solar-wind hybrids have high-capacity factors, less power swings, and more dependable electricity as compared to single-source systems. Battery-based storage also enhances continuity of energy by offsetting intermittent changes in the solar irradiance and wind velocity [18–21].

Vertical axis wind turbines (VAWTs) are typically used in small-scale and urban hybrid systems because they can start automatically in low-wind conditions, maintain efficiency in turbulent wind conditions, and their mechanical construction is straightforward [19–23]. Drag based VAWTs have lower aerodynamic efficiencies than lift based horizontal axis turbines, but their resilience, ease of repair and ability to install in a decentralized configuration make them an appealing choice in a combined hybrid system [24–26].

Photovoltaic (PV) systems with battery storage are widely applied to off-grid systems. Nonetheless, their output is limited in prolonged phases of low solar radiant and this highlights the necessity of supplementary wind energy [27–31].

Small-scale conversion of wind energy requires mechanical transmission systems such as spur gears to accelerate the rotational velocity of generators when the turbine speed is inadequate to directly drive the generators [32,33]. Although there are a lot of experimental studies on hybrid systems, very few of them present a comprehensive framework of a design and fabrication-based on CAD, field installation, and experimental validation of such systems under real outdoor conditions, both in

highways and in rural areas. This study fills such a gap by providing a completely integrated system, between design and experimental analysis within the scope of proving practical feasibility of decentralized power generation.

System Configuration and Working Principle

The hybrid solar-wind energy system combines the VAWT and PV panel as supplementary renewable energy sources. The wind turbine starts slowly and be able to operate in turbulent flow, whereas the PV array is mounted at an angle that maximizes the capture of solar irradiance. Both sources are connected to one central energy storage and control subsystem that consists of a deep-cycle battery and a charge controller that controls the voltage, eliminates overcharging and over-discharge. The energy stored is used to supply low-voltage DC loads, mostly LED lights, to maintain sustained and stable power supply to the loads even when environmental conditions vary. The system flow chart (Figure 1) indicates the overall system structure with one block representing the wind energy subsystem, the other is the PV subsystem, and both feed the energy storage which subsequently powers the electrical loads.

The wind energy conversion subsystem uses VAWT through four semi-cylindrical shaped PVC blades mounted in a symmetric arrangement on a vertical shaft. When the blades are subjected to the wind, rotation is caused by the difference between concave and convex surfaces drag. End bearings on each side of the shaft minimize friction and allow the machine to rotate freely, and a spur gear system with a pinion ensures a faster rate of rotation of the generator, so the generator is able to produce power even when the wind is slow. A frame made of mild steel is used to accommodate the turbine assembly to ensure structural stability. Table 1 summarizes the main geometrical parameters and structure of the turbine.

Table 1. Turbine Dimensions and Configuration

Parameter	Value	Unit
Blade Height (H)	0.6096	m
Blade Diameter (D)	0.152	m
Blade Thickness (t)	0.003	m
Rotor Radius (R)	0.076	m
Number of Blades (n)	4	–
Hub Diameter	0.05	m
Material	PVC	–

The PV subsystem transforms the sunlight into direct current electricity and it has blocking diodes to avoid the flowing of reverse current in case of low irradiance or during the night operation. The deep-discharge battery accumulates electrical energy generated from the two sources, that is controlled by the battery charge regulator. This hybrid structure provides continuous and steady power supply to the low-voltage DC loads, and therefore can be used in the decentralized applications like highway lighting and rural electrification. The modular construction enables the scalability and

enhanced reliability of the modular systems over standalone renewable systems.

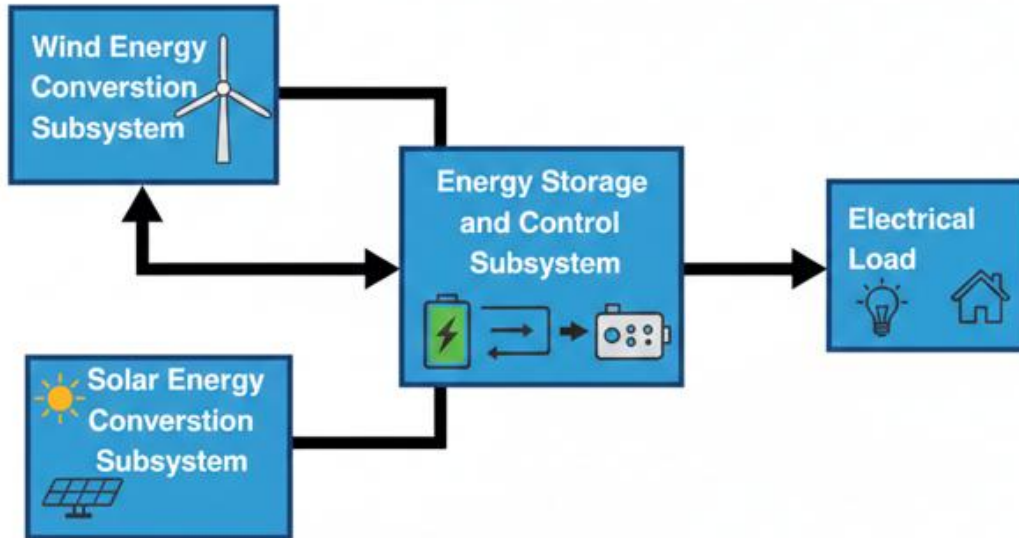


Figure 1. Block Diagram of the Hybrid Solar–Wind Energy System

Methodology

The approach in this study comprises of the hybrid design, 3D modeling, construction, and experimental analysis of a solar–wind hybrid system. The research strategy provides an accurate component design, system assembly, and ensure good performance evaluation in the actual environment. Experiments were also done outside to test the power generation, rotational speed of the turbine, battery charging behavior, and stability of the whole operation under different wind and solar conditions.

Theoretical Modeling of Wind Subsystem

The wind energy subsystem operates on a VAWT whose four semi-cylindrical blades are made of PVC and are attached to a vertical shaft in a symmetrical fashion. The difference in the drag between the concave and convex face of the turbine blades produce rotational movement as a result of wind on the turbine blades.

Kinetic energy of air flowing on the rotor is calculated as:

$$K. E_{\text{air}} = 0.5mv^2 \quad (1)$$

Wind power available is given as:

$$P_w = 0.5\rho Av^3 \quad (2)$$

where ρ is air density (kg/m^3), A is the rotor swept area (m^2), and v is wind speed (m/s). The tip speed ratio (λ) defines the relation between blade tip velocity and wind speed:

$$\lambda = \omega R/v \quad (3)$$

where ω is the turbine angular velocity (rad/s) and R is the rotor radius (m). The aerodynamic conversion efficiency is defined by the turbine power coefficient (C_p). Drag-based VAWTs operate at levels below Betz's limit (0.593) owing to their design.

Blade Properties and Aerodynamics

Table 2 provides the geometric and material properties of the turbine blades. Aerodynamic behavior is characterized by Reynolds number and solidity of the turbine.

Table 2. Blade and Material Properties

Parameter	Value	Unit
Material	PVC	–
Blade Height (H)	0.6096	m
Blade Diameter (D)	0.152	m
Blade Thickness (t)	0.003	m
Density	1400	kg/m ³
Young's Modulus	3×10^3	MPa
Poisson Ratio	0.35	–
Specific Heat	1500	J/kg-K
Rotor Radius (R)	0.076	m
Number of Blades (n)	4	–
Hub Diameter	0.05	m

Reynolds number is calculated as:

$$Re = (lv)/\nu \quad (4)$$

where l is blade chord length, v is wind speed, and $\nu = 15.11 \times 10^{-6} \text{ m}^2/\text{s}$ is the kinematic viscosity of air. Solidity (σ) is expressed as:

$$\sigma = (nl)/(2\pi R) \quad (5)$$

The forces in the blades are calculated as follows:

$$W_t = \cos \theta + \omega R \quad (6)$$

$$W_R = \sin \theta + V \quad (7)$$

$$A = \sqrt{(W_R^2 + W_t^2)} \quad (8)$$

where W_t is the tangential component, W_R is the radial component, and θ is the azimuth angle of the rotor.

Performance Parameters

Summary of the key performance parameters of the turbine in the experimental settings is provided in Table 3.

Table 3. Wind Turbine Performance Parameters

Parameter	Formula	Value	Unit
Kinetic Energy of Air	$K \cdot E_{\text{air}}$	4.875	J
Power of Wind Turbine	P	1.225	W
Mass Flow Rate	$\dot{m}$	0.098	kg/s
Available Wind Power	P_a	4.843	W

Parameter	Formula	Value	Unit
Force on Rotor	F	0.9686	N
Torque on Rotor	T	0.291	N-m
Swept Area	A_s	0.000314	m ²

Mechanical Transmission Design

A spur gear and pinion give the DC generator a higher rotational speed, and is important to generate efficient energy conversion when the turbine runs slowly. Table 4 gives the parameters of gear design.

Table 4. Spur Gear and Pinion Parameters

Parameter	Gear (N=40)	Pinion (N=12)	Unit
Pitch Diameter	51.2	16.2	mm
Module	1.28	1.35	mm
Addendum	1.28	1.35	mm
Dedendum	1.481	1.562	mm
Clearance	0.201	0.212	mm
Outside Diameter	53.76	18.9	mm
Working Depth	2.761	2.911	mm
Tooth Thickness	2.011	2.121	mm

The spur gear and pinion arrangement are used to connect the turbine shaft to the DC generator to provide constant torque transmission with high efficiency at low wind speeds.

Photovoltaic Subsystem and Energy Storage

The PV array transforms solar radiation to direct current electricity and the blocking diodes stop reverse current at low irradiance. The turbine and the PV array generate electrical energy which is stored in a deep-cycle battery and controlled by a charge controller to avoid overcharging. The energy is stored as low-voltage DC that drives low-voltage DC loads like LED lighting and allows it to operate continuously when the environmental conditions vary.

Materials, CAD Design, and Fabrication

The system was designed by using well-chosen materials, CAD-based modeling, and the accurate fabrication to guarantee structure stability, mechanical stability, and effective conversion of energy under the outdoor environment. The turbine blades were made of PVC due to their low weight, resistance to corrosion, ability to withstand varying weather conditions, and easy manufacturability. The supporting frame and vertical shaft were fabricated using mild steel to offer rigidity and a stable support. The spur gear and pinion were made out of hardened steel in order to transmit torque efficiently between the turbine shaft and the DC generator. End steel

bearings were fitted with rubber seals at each end of the shaft to minimize the friction and provide smooth rotation. The deep-cycle battery and the PV array made the hybrid energy conversion and storage subsystems complete.

All mechanical components were simulated using commercial 3D CAD software to produce precise geometry, execute assembly simulation, and validate clearances ahead of fabrication. CAD modeling was used to ensure that the turbine blades, shaft, arms and gear-pinion assembly were properly aligned and also gave a digital view of the entire system. The turbine, PV panel, and battery are mounted on the main frame, and the base is used to ensure stability over a stable installation. The prime mover shaft drives the turbine blades through the spur gear and pinion to accelerate the speed of the generators, so that it can generate electricity effectively even when the wind is very low. The four semi-cylindrical blades are attached to the central shaft with turbine arms that ensure the ideal positioning of the blades to initiate self-starting and operate effectively. Table 5 depicts the system components, their base materials, operational functions, and suitable parametric modeling and production notes.

Table 5. Components, Materials, and Functions

Component	Material	Function/Role	CAD/Fabrication Notes
Main Frame	Mild Steel	Structural support for turbine, PV, and battery	Modeled in CAD; welded and machined
Base	Mild Steel	Provides stability and secure site mounting	CAD-verified; welded
Prime Mover Shaft	Mild Steel	Transfers turbine rotation to gear-pinion assembly	Machined for bearings; CAD-aligned
Turbine Arm	Mild Steel	Connects blades to shaft, maintains orientation	CAD-modeled; welded to shaft
Turbine Blades	PVC	Converts wind energy to rotational motion	CNC-cut; four semi-cylindrical blades
Spur Gear	Hardened Steel	Transmits torque to pinion, increases generator speed	CAD-modeled; precision cut
Pinion	Hardened Steel	Mated with gear for torque transmission	CAD-modeled; mounted to generator
Bearings	Steel/ rubber seals	Reduce friction, support smooth rotation	Selected to match shaft diameter
PV Panel	Crystalline Silicon	Converts solar radiation to DC electricity	Standard module; CAD-positioned for tilt
Battery	Lead-Acid Deep-Cycle	Stores energy from wind and solar subsystems	Integrated in frame; voltage monitored

The fabrication process included precision machining of PVC turbine blades, machining and fusion welding of the shaft, base frame and rotor arms, and high precision assembly of the spur gear transmission system with the DC generator. The frame was designed to hold the PV array and battery to keep a modular design and

stability of the structure. The complete system was installed successfully on a highway which proved to have reliable power delivery and can carry out its operation fairly well with the fluctuating wind and solar conditions.

Figure 2-8 present CAD models of separate components, such as the main frame, base, turbine shaft, arms, blades and gear-pinion assembly while figure 9 presents the complete CAD model of the hybrid system. The fabricated prototype is shown in figure 10. This integrated design, choice of materials and fabrication method led to a strong scalable hybrid energy system that can be used in a decentralized application like rural electrification and highway lighting.

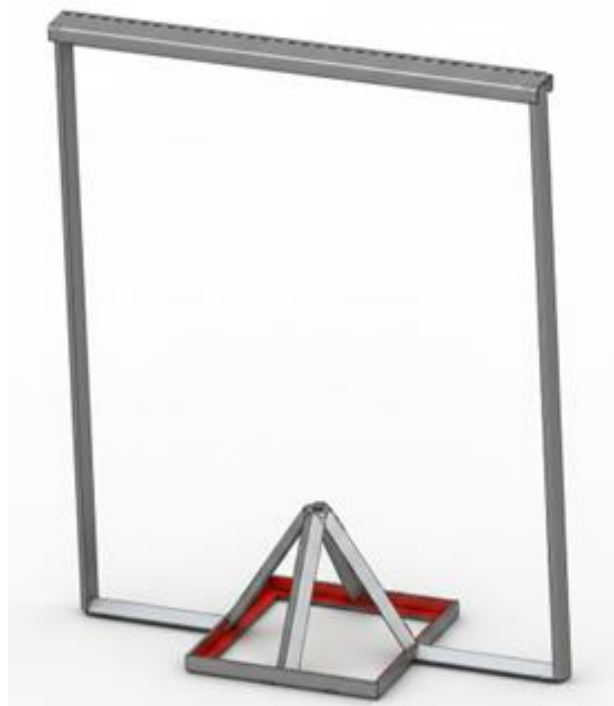


Figure 2. CAD Model of Main Frame



Figure 3. CAD Model of Base

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Figure 4. CAD Model of Turbine Shaft



Figure 5. CAD Model of Turbine Arm



Figure 6. CAD Model of Wind Turbine Blades

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Figure 7. CAD Model of Gear



Figure 8. CAD Model of Pinion

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Figure 9. Complete CAD Model



Figure 10. Fabricated Prototype of the Hybrid Solar-Wind Energy System showing Complete Assembly

Experimental Setup

The system was experimented on a highway under actual outdoor conditions to test the working performance, electrical output and the behavior of the battery charging. The prototype was a combination of a VAWT, a photovoltaic panel, a deep-cycle battery, and a charge controller that provided low-voltage DC loads. The installation of the system was such that the turbine was optimally exposed to the wind and that the PV array was minimally shaded to maximize the energy of both renewable energy sources. The objectives of the experiments were to test turbine self-starting, efficiency of the generator, battery charge regulation and the capabilities to provide constant power to 4-5 LED loads at changing environmental conditions.

The measurements of mechanical and electrical parameters were taken by using calibrated instruments. The speed of wind was measured using the anemometer, rotational speed of the turbine using the tachometer, voltage and current using the multimeter, and the solar irradiance using the pyranometer (Table 6). Electrical energy of both wind and solar subsystems was connected to the charge controller into the battery and the LED loads were used as real time indicators of energy delivery and system stability. This system enabled a thorough assessment of the performance of the hybrid system at various times of the day and under varying wind conditions.

Table 6. Measurement Instruments

Instrument	Parameter Measured	Range
Anemometer	Wind speed	0–30 m/s
Pyranometer	Solar irradiance	0–1000 W/m ²
Tachometer	Turbine rotational speed	0–3000 rpm
Multimeter	Voltage, Current	0–20 V, 0–10 A

This experimental setup allowed gathering of fine performance data, such as the rotational speed of the turbine, electrical power discharged by wind and solar power and battery voltage dynamics. The findings indicate that the hybrid system offers stable and constant power to small scale application like highway lighting and rural electrification, where the PV array contributes most of the energy in the day time and the wind turbine in the low to moderate wind conditions charges the battery.

Results

The solar-wind energy system was tested under the actual outdoor conditions on a highway and measurements were taken over a few days to measure the changing wind and solar conditions. The rotational speed of the turbines was 30 to 180 rpm when the wind speed was 2.5 to 7 m/s. In bright sunshine (approximately 900 W/m²) the PV array was capable of generating a maximum voltage of 12.8 V, whereas the voltage of the battery measured between 11.5 V and 12.8 V in integration.

The system provided sustained power that was enough to power 4-5 LED lights (3 W each) at a time. Combined electric power was about 18-20 W under favorable wind and sun conditions, and the solar array was able to provide most of the energy when there were bright daylight and the wind turbine assisted in recharging the battery

when there was poor sun exposure. The system ensured constant voltage rates and constant operation which proves efficient energy management and supply of the load under changing environmental conditions. The operational performance is summarized in Table 7.

Table 7. Summary of Measured Electrical Performance

Parameter	Value	Unit
Maximum Turbine Speed	180	rpm
Maximum PV Voltage	12.8	V
Battery Voltage Range	11.5–12.8	V
Maximum Electrical Power Output	18–20	W
Number of LED Loads Powered	4–5	–

Discussion

The experiment findings affirm that the combination of wind and solar sources contributes to the continuity of energy compared to independent systems. The wind turbine functions efficiently at small to moderate wind velocities, while the photovoltaic unit provides steady energy during hours of sunlight. The combination is such that the battery is charged and the LED loads work continuously even when the solar irradiance is low or when the wind is not blowing.

A spur gear and pinion system enhanced the rotational speed of the generator when there was low wind and it was a better way of increasing the efficiency of the turbine and providing enough power to satisfy the load demands. Its modular design can be easily scaled with the additional loads or expanded installations. Battery voltage was in the safe operating range and it shows that the charge controller successfully managed power between the two sources to avoid overcharging or deep discharge.

Comprehensively, the system is appropriate in decentralized applications, including highway lighting and rural electrification, where a dependable, cost-effective, and scalable solution is required. The environmental variations are the key factors behind the minor changes in power output, and hybridization is essential to ensure the stability of the load. The findings confirm the design and justify its effective implementation on highways or in the off-grid communities.

Conclusion

The evidence from the research suggests that a hybrid solar wind energy system can provide steady decentralized power to highway lighting. The installed and designed system presented a combination of VAWT, photovoltaic panel, deep cycle battery and a spur gear pinion mechanism. It was able to continuously energize 4 to 5 LED lights during the varying weather conditions.

The results of the experiment reveal that the photovoltaic panel provided the majority of energy when the sun was shining. The wind turbine assisted in charging battery at the time of low sunlight. This interaction provided uninterrupted power supply. Voltage and current were controlled efficiently by the charge controller and battery. They helped them avoid overcharging and deep discharge. The combined electrical

power was approximately 18 to 20 W. This production satisfied the lighting requirements.

The findings demonstrate clearly that hybrid operation enhances energy continuity and load reliability, as opposed to single source systems. Its modular and scalable architecture is useful in off grid rural electrification and highway infrastructure. The system provides low cost, powerful and environmentally friendly solution to small scale applications.

Some limitations remain like the contribution of wind energy was comparatively small which enhanced reliance on solar power. The system does not have sophisticated control capabilities like maximum power point tracking and dynamic load regulation. Extreme weather and seasonal variation performance was not tested in the long term.

Future research must aim at enhancing the design of turbine blades to enhance low wind performance. Transmission losses due to mechanical means should be minimized. High level power electronics would be incorporated to enhance energy capture. Assessment and testing should be done on higher capacity and long-life batteries. Long-field testing is needed to test durability, reliability, and maintenance requirements. Such measures will facilitate the system to carry higher loads and enhance its functions in sustainable decentralization of power generation.

REFERENCES

- Li, M., Li, L. & Strielkowski, W. The Impact of Urbanization and Industrialization on Energy Security: A Case Study of China. *Energies* **12**, 2194 (2019).
- Kunwal, I., Sheikh, M. R., Faridi, M. Z. & Mushtaq, M. I. Urbanization, Energy Consumption and Environmental Quality in Asian Countries. *Bull. Bus. Econ. BBE* **12**, 372–386 (2023).
- Shahbaz, M., Chaudhary, A. R. & Ozturk, I. Does urbanization cause increasing energy demand in Pakistan? Empirical evidence from STIRPAT model. *Energy* **122**, 83–93 (2017).
- Population–Urbanization–Energy Nexus: A Review. <https://www.mdpi.com/2079-9276/8/3/136>.
- Gao, C. & Chen, H. Electricity from renewable energy resources: Sustainable energy transition and emissions for developed economies. *Util. Policy* **82**, 101543 (2023).
- Decarbonization of the electricity generation sector and its effects on sustainability goals | Sustainable Energy Research | Springer Nature Link. <https://link.springer.com/article/10.1186/s40807-023-00080-1>.
- Environmental Impact of Electricity Generation Technologies: A Comparison between Conventional, Nuclear, and Renewable Technologies. <https://www.mdpi.com/1996-1073/16/23/7847>.
- Yang, X. & Long, L. Renewable energy transition and its implication on natural resource management for green and sustainable economic recovery. *Resour. Policy* **89**, 104624 (2024).
- DESIGN AND EXPERIMENTAL EVALUATION OF A SOLAR ASSISTED ELECTRIC VEHICLE PROTOTYPE | Spectrum of Engineering Sciences. <https://www.thesesjournal.com/index.php/1/article/view/1824>.

- Chen, G. & Ji, Z. A Review of Solar and Wind Energy Resource Projection Based on the Earth System Model. *Sustainability* **16**, 3339 (2024).
- Hamed, T. A. & Alshare, A. Environmental Impact of Solar and Wind energy- A Review. *J. Sustain. Dev. Energy Water Environ. Syst.* **[10]**, [1]-[23] (2022).
- Determinants of Renewable Energy Technology Deployment: A Systematic Review. <https://www.mdpi.com/2071-1050/17/23/10538>.
- Nogueira, C. E. C. et al. Sizing and simulation of a photovoltaic-wind energy system using batteries, applied for a small rural property located in the south of Brazil. *Renew. Sustain. Energy Rev.* **29**, 151–157 (2014).
- Sanchez-Alfaro, P. et al. Geothermal barriers, policies and economics in Chile – Lessons for the Andes. *Renew. Sustain. Energy Rev.* **51**, 1390–1401 (2015).
- Schleifer, A. H., Harrison-Atlas, D., Cole, W. J. & Murphy, C. A. Hybrid renewable energy systems: the value of storage as a function of PV-wind variability. *Front. Energy Res.* **11**, (2023).
- Thanasekaran, N. & Murugan, A. A Comprehensive Review of Hybrid Renewable Energy Systems: Advances in Wind-Solar Integration, Optimization, and Energy Storage Solutions. *Int. J. Progress. Res. Sci. Eng.* **6**, 18–23 (2025).
- Solar–wind hybrid renewable energy system: current status of research on configurations, control, and sizing methodologies. in *Hybrid-Renewable Energy Systems in Microgrids* 219–248 (Woodhead Publishing, 2018). doi:10.1016/B978-0-08-102493-5.00012-1.
- Buonomano, A., Calise, F., d’Accadia, M. D. & Vicidomini, M. A hybrid renewable system based on wind and solar energy coupled with an electrical storage: Dynamic simulation and economic assessment. *Energy* **155**, 174–189 (2018).
- Alkhafa, A., Kadhim, M. G., alhaddad, F. A. & Saad, A. Performance analysis of hybrid renewable energy systems under variable operating conditions. *Sol. Compass* **15**, 100134 (2025).
- A fuzzy logic based energy management model for solar PV-wind standalone with battery storage system | Scientific Reports. <https://www.nature.com/articles/s41598-025-09662-z>.
- Optimal dimensioning of grid-connected PV/wind hybrid renewable energy systems with battery and supercapacitor storage a statistical validation of meta-heuristic algorithm performance - PMC. <https://pmc.ncbi.nlm.nih.gov/articles/PMC12753802/>.
- Kumar, R., Raahemifar, K. & Fung, A. S. A critical review of vertical axis wind turbines for urban applications. *Renew. Sustain. Energy Rev.* **89**, 281–291 (2018).
- Capacity configuration strategy for wind-photovoltaic-battery system based on optimized simulated annealing | International Journal of Low-Carbon Technologies | Oxford Academic. <https://academic.oup.com/ijlct/article/doi/10.1093/ijlct/ctad113/7595594>.
- Aerodynamic Performance of Vertical-Axis Wind Turbines. <https://www.mdpi.com/2077-1312/11/7/1367/xml>.
- A comprehensive review on various approaches for performance improvement of Savonius wind turbines | Discover Applied Sciences | Springer Nature Link.

https://link.springer.com/article/10.1007/s42452-025-07627-5?utm_source=chatgpt.com.

A Review of the Effects of Key Parameters on the Performance of Horizontal and Vertical Axis Wind Turbines | IIETA.
<https://iieta.org/journals/jesa/paper/10.18280/jesa.580713>.

Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M. & Jaszczur, M. A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. Results Eng. **20**, 101621 (2023).

Comparative Analysis of PV and Hybrid PV–Wind Supply for a Smart Building with Water-Purification Station in Morocco. <https://www.mdpi.com/2071-1050/17/19/8604>.

Optimal design of an off-grid hybrid renewable energy system considering generation and load uncertainty: the case of Zanzan city, Iran | Discover Applied Sciences | Springer Nature Link. <https://link.springer.com/article/10.1007/s42452-021-04718-x>.

Hybrid Renewable Energy Systems for Off-Grid Electrification: A Comprehensive Review of Storage Technologies, Metaheuristic Optimization Approaches and Key Challenges. <https://www.mdpi.com/2673-4117/6/11/309>.

Staden, P., Adefarati, T., Naidoo, R. & Bansal, R. Design and Analysis of an Off-Grid Connected PV- Wind-Battery Hybrid Energy System. (2022). doi:10.1109/GlobConET53749.2022.9872417.

Calautit, K. & Johnstone, C. State-of-the-art review of micro to small-scale wind energy harvesting technologies for building integration. Energy Convers. Manag. X **20**, 100457 (2023).

Ragheb, A. & Ragheb, M. Wind Turbine Gearbox Technologies. Proceedings of the 1st International Nuclear and Renewable Energy Conference vol. 8 8 (2010).