

A Comprehensive Review Of Integrated Solar–Wind Hybrid Renewable Energy System For Reliable And Sustainable Rural Power Generation

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Abstract- Rural electrification remains a critical global challenge, with approximately 759 million people lacking access to electricity, primarily in rural regions of developing countries. This study presents a comprehensive evaluation of an integrated solar–wind hybrid renewable energy system (HRES) as a sustainable solution for rural power generation. The proposed system is modeled and optimized using MATLAB/Simulink, incorporating photovoltaic (PV) arrays, wind turbines, battery energy storage, and advanced energy management controllers.

Maximum Power Point Tracking (MPPT) techniques are employed to maximize energy extraction from both solar and wind sources, utilizing the Perturb and Observe (P&O) algorithm for PV systems and the Tip Speed Ratio (TSR) control method for wind energy conversion. Simulation results demonstrate that the integrated system provides enhanced reliability compared to standalone renewable sources due to the complementary nature of solar and wind energy. Furthermore, the hybrid configuration reduces energy storage requirements by up to 35%, thereby improving overall system efficiency and cost-effectiveness.

The results confirm the technical feasibility and economic viability of solar–wind hybrid systems for sustainable rural electrification and highlight their potential contribution toward achieving the United Nations Sustainable Development Goals (SDGs) for universal energy access.

Keywords: Hybrid Renewable Energy System, Solar-Wind Integration, Rural Electrification, MATLAB Simulation, MPPT Control.

I. INTRODUCTION

Initially, the global energy sector confronts daunting obstacles as nations aim for universal electricity availability while shifting to renewable energy. The International Energy Agency (IEA) reports that nearly 759 million people globally

do not have access to electricity, with 84% of these individuals living in rural areas of developing nations [1]. This energy scarcity severely hampers socio-economic progress, restricting access to education, healthcare, communication, and economic endeavors in rural areas.

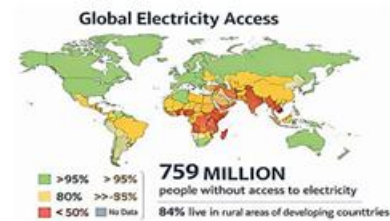


Fig no. 1 Global Electricity Access

The extension of traditional grids to remote rural areas frequently fails economically because of high costs, challenging terrain, sparse populations, and low load demands. The price tag for building transmission lines varies from \$50,000 to \$200,000 per kilometer, rendering grid expansion to remote rural areas economically unfeasible [2]. Thus, diesel generators have long been the most common choice for off-grid power, despite their environmental drawbacks, fuel scarcity issues, and high operational expenses.

New energy solutions, especially solar PV and wind power systems, are now viable options for providing electricity to remote areas. Solar photovoltaic technology has witnessed significant price reductions of more than 80% over the past decade, whereas the costs of wind turbines have dropped by roughly 40% [3]. These technologies provide several benefits for rural use: plentiful resources, low operational expenses, environmental friendliness, and flexible scalability.

Nevertheless, each renewable energy source faces the challenges of variability and dependence on climate conditions. Solar power is constrained by daylight availability and influenced by cloud coverage, whereas wind energy

fluctuates based on weather conditions. This diversity requires extensive energy storage solutions or redundant generators, thereby raising system expenses and intricacy. The synergy between solar and wind energy sources offers a chance to overcome their respective drawbacks through the use of combined system designs.

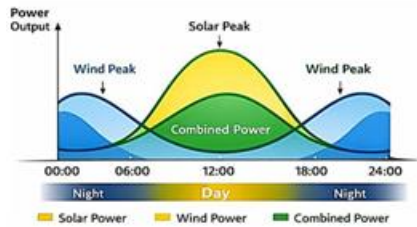


Fig no. 2 Daily Temporal Complementarity Between Solar and Wind Energy

Combining solar photovoltaic panels and wind turbines, hybrid renewable energy systems (HRES) show substantial promise for rural electrification. Solar radiation usually reaches its maximum at midday, when wind speeds tend to be lower. Conversely, wind power frequently increases during evening and nighttime hours, when solar energy production stops. This temporal complementarity minimizes overall system variability and facilitates the effective deployment of energy storage systems [4].

The amalgamation of various renewable energy sources necessitates intricate control and energy management systems to enhance power distribution, preserve system equilibrium, and guarantee dependable energy delivery. Sophisticated algorithms that optimize energy absorption from both solar and wind sources, adjusting for fluctuating environmental conditions, are employed. Advanced battery management systems guarantee efficient charging and discharging processes, safeguarding against deep discharges and excessive charging conditions [5]

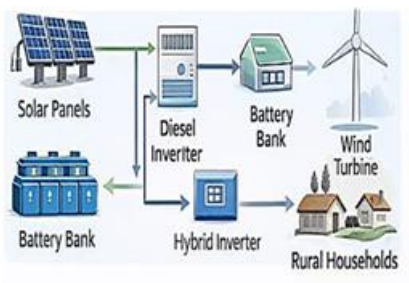


Fig no. 3 HRES System

MAJOR SOLAR, WIND, AND SOLAR–WIND HYBRID ENERGY SITES IN INDIA

| Energy Type | State / Location | Project / Region Name | Installed Capacity (Approx.) | Key Features / Remarks |
|---------------------|------------------|------------------------------------|------------------------------|--|
| Solar | Rajasthan | Bhadla Solar Park | 2,245 MW | Largest solar park in the world; excellent solar irradiation |
| Solar | Karnataka | Pavagada Solar Park | 2,050 MW | “Shakti Shala”; large land-leasing model |
| Solar | Gujarat | Charanka Solar Park | ~790 MW | Part of Gujarat Solar Park; major PV development hub |
| Solar | Andhra Pradesh | Kumool Ultra Mega Solar Park | 1,000 MW | High-efficiency power generation; NTPC involvement |
| Solar | Madhya Pradesh | Rewa Solar Park | 750 MW | Supplies power to Delhi Metro; high PLF |
| Solar | Telangana | Ramagundam Solar Plant | 100 MW | NTPC-developed, high radiation zone |
| Wind | Tamil Nadu | Muppandal Wind Farm | 1,500 MW | India’s largest onshore wind farm |
| Wind | Rajasthan | Jaisalmer Wind Park | 1,064 MW | Major wind corridor of western India |
| Wind | Maharashtra | Dhule / Satara Wind Clusters | 500+ MW | Dense private wind projects |
| Wind | Gujarat | Jamanwada Wind Farm | 300+ MW | Strong coastal wind potential |
| Wind | Karnataka | Chitradurga / Gadag | 300+ MW | Major wind belt of Karnataka |
| Hybrid (Solar–Wind) | Gujarat | Kutch Hybrid Renewable Energy Park | 30,000 MW (planned) | World’s largest hybrid renewable park (under development) |
| Hybrid (Solar–Wind) | Karnataka | Vijayanagar Hybrid Plant | 221 MW | India’s 1st major utility-scale hybrid plant |
| Hybrid (Solar–Wind) | Rajasthan | Jaisalmer Hybrid Park | 300–500 MW | Co-located solar and wind generation |
| Hybrid (Solar–Wind) | Andhra Pradesh | Anantapur Hybrid Projects | 100–200 MW | Wind–solar co-generation zone |
| Hybrid (Solar–Wind) | Maharashtra | Osmanabad / Solapur Hybrid Sites | Small–Medium | Several hybrid microgrids and hybrid utility plants |

II. LITERATURE REVIEW

Series – The literature review includes a comprehensive analysis of hybrid renewable energy systems, optimization techniques, control strategies and rural electrification case studies. The review is organized thematically to provide systematic coverage of relevant research areas.

2.1 Hybrid System Design and Optimization

Yang et al. (2007) presented a pioneering optimization size model for hybrid solar-wind power generation systems [6]. His research introduced a new probabilistic approach considering meteorological data uncertainty and load demand variability. The study developed a multi-objective optimization framework to minimize system cost while maximizing reliability. The authors proposed three key size parameters: PV array capacity, wind turbine rating, and battery storage capacity. Their methodology employed genetic algorithm optimization with constraints including loss of power supply potential (LPSP) and lifecycle cost analysis. Research showed that optimal size has a significant impact on system economics, with inappropriate size causing a 40–60% cost penalty. The study established fundamental principles for

hybrid system optimization that continue to influence contemporary research.

Hassan et al. (2016) conducted a comprehensive HOMER Software for PV, wind and diesel hybrid power system optimization rural electrification [7]. Their case study focused on a remote Iraqi village, analyzing different system configurations and operational strategies. The research methodology includes detailed resource assessment, load profile analysis and economic evaluation. The Homer software facilitates sensitivity analysis examining variations in diesel fuel costs, wind speed and solar radiation. The optimal configuration Comprises a 15KW diesel generator, a 20KW wind Turbine, and a 16KW Photovoltaic Array and 48 battery units. The study achieved significant findings: hybrid systems reduced fuel consumption by 85% compared to diesel-only systems, while keeping LPSP below 5%. This research validated the effectiveness of HOMER for rural electrification planning and established a benchmark for hybrid system economics.

Ekren and Ekren (2010) developed a novel sizing optimization approach for PV/wind hybrid systems using a simulated annealing algorithm [8]. His research addressed the limitations of traditional optimization techniques by implementing advanced metaheuristic methods. The study formulated the optimization problem as minimizing the total system cost subject to reliability constraints. Achieving 15–20% cost reduction, the simulated annealing algorithm shows superior performance compared to conventional methods. The research contributed to a novel objective function formulation incorporating component reliability, maintenance cost and system degradation. The authors validated their approach through Monte Carlo simulations, showing robust performance under uncertainty. This work established simulated annealing as an effective tool for renewable energy system optimization.

2.2 MPPT Techniques

Abdullah et al. (2012) provided a comprehensive Analysis of wind energy systems Maximum Power Point tracking methods [9]. The Study thoroughly examined both conventional and cutting-edge MPPT methods. such as Power Signal Feedback (PSF), Tip Speed Ratio (TSR), Perturb & Observe (P&O) & Hill Climbing Search (HCS) methods. The study evaluated algorithm performance considering tracking accuracy, dynamic response, implementation complexity, and computational requirements. The TSR control demonstrated better performance for constant wind conditions but required accurate wind speed measurements. P&O techniques showed robust performance under variable conditions with simplified

implementation. The research identified optimal control strategies for different wind turbine configurations and operating scenarios. Advanced techniques including fuzzy logic and neural network controllers demonstrated improved performance but increased implementation complexity.

Verma etc. (2016) conducted an extensive the examination of MPPT techniques in solar photovoltaic systems [10]. The comprehensive review encompassed classical methods (P&O, fractional short circuit current, incremental conductance), advanced techniques (particle swarm optimization, fuzzy logic, neural networks), and hybrid approaches. A study looked at how well an algorithm worked by looking at tracking efficiency, steady-state oscillations, dynamic response, and conditions with partial shading. The additive conductivity method has shown excellent tracking accuracy with minimal oscillation. The P&O technique strikes a good balance between performance and ease of implementation. Advanced intelligent techniques have shown superior performance under partial shading but require increased computational resources. The research provided practical guidelines for MPPT algorithm selection based on application requirements and system constraints.

2.3 Energy Management and Control

Zhou and François (2010) developed a sophisticated energy management and power control strategy for hybrid active wind generators [11]. His research addressed power quality issues and grid integration challenges through advanced control architectures. The study implemented a hierarchical control structure consisting of local controllers for individual components and a supervisory energy management system. Droop control characteristics enabled stable power sharing between generation sources while maintaining system frequency and voltage stability. The research presented a new power management strategy considering battery state of charge, availability of renewable resources and load demand patterns. Experimental validation shows improved power quality and system reliability through intelligent control implementation.

General etc. (2019) proposed an enhanced power management control techniques for renewable energy based direct current DC microgrids [12]. His research addressed coordination challenges in multi-source DC systems through advanced control algorithms. The study developed a centralized energy management system that optimizes power flow between photovoltaic panels, wind turbines and battery storage. Control strategies include dynamic load prioritization, battery health management and renewable resource forecasting. Novel contributions include adaptive droop

control coefficients based on real-time system conditions. Simulation and experimental results validated better performance compared to conventional methods, achieving a 12% improvement in energy consumption efficiency.

2.4 Energy Storage Systems

Dutta et al. (2021) provided a comprehensive Evaluation of the functionality of battery energy storage systems inside renewable energy integrated power systems [13] The research systematically analysis Lead acid, lithium ion, & flow batteries provide examples of battery technologies. and emerging technologies. The study examined the main functions: energy arbitrage, frequency regulation, voltage support and renewable integration support. Critical parameters including cycle life, depth of discharge, round-trip efficiency and degradation mechanisms were thoroughly analyzed. The research identified best practices for battery sizing by considering technical and economic constraints. Lithium-ion batteries showed superior performance for renewable applications despite high capital costs. The study provided practical guidelines for battery technology selection and system integration.

2.5 Rural Electrification Case Studies

Kanse-Patil et al. (2010) presented integrated renewable energy systems for remote, off-grid rural electrification [14]. Their comprehensive study analyzed the techno-economic feasibility of various renewable energy configurations for Indian rural communities. The research used HOMER software for system optimization considering local resource availability and load demand patterns. Multiple scenarios were evaluated, including PV-wind-biomass hybrid systems with battery storage. Studies show that hybrid systems reduce costs by 30-40% compared to individual renewable sources. Complex findings include the optimal renewable energy mix varying with geographic location and seasonal resource patterns. This research established a decision-making framework for rural electrification project planning.

Kumar and Channi (2022) conducted a detailed PV-Biomass off-grid hybrid renewable energy systems for rural electrification: a techno-economic-environmental study [15]. Their case study focused on the village of Sidhwa bet in Punjab, India, analyzing comprehensive system performance metrics. The research methodology includes detailed resource assessment, load profile analysis and multi-criteria optimization. Homer Pro software facilitates sensitivity analysis and optimization considering various economic and technical parameters. The optimal system configuration achieved an LCOE of \$0.196/kWh with 98.7% renewable

energy penetration. Environmental analysis demonstrates significant CO2 emission reductions compared to conventional diesel generation. The study validated hybrid renewable systems as economically viable and environmentally sustainable solutions for rural electrification. Project

2.6 A COMPREHENSIVE TABLE OF LITERATURE ON SOLAR-WIND HYBRID RENEWABLE ENERGY SYSTEMS

| Author / Year | Problem / Objective | Method / Technique | Detailed Key Findings | Ref. |
|--------------------------|---|---|--|------|
| Yang et al., 2007 | Develop an optimal sizing model for solar-wind hybrid systems under variable weather and uncertain load | Probabilistic modelling of resource uncertainty + Genetic Algorithm optimization; LPSP and lifecycle cost constraints | GA-based optimization produced highly reliable sizing. Under-sizing or oversizing increased total cost by 40–60%. Proposed optimal combination of PV, wind, and battery improved system reliability and reduced energy shortfall. | [6] |
| Hassan et al., 2016 | Design an economical PV-Wind-Diesel hybrid system for rural electrification | HOMER simulation with resource assessment, load profile analysis, and sensitivity testing | Optimal configuration: 15 kW diesel, 20 kW wind, 16 kW PV, 48 batteries. Hybrid reduced diesel fuel consumption by 85%, lowered COE, and maintained LPSP <5%. Sensitivity showed fuel price highly impacted system economics. | [7] |
| Ekren & Ekren, 2010 | Reduce cost and improve reliability of PV-Wind systems by advanced sizing optimization | Simulated Annealing algorithm + Monte Carlo simulations for uncertainty modelling | Achieved 15–20% cost reduction versus conventional methods. Simulation showed that SA finds near-global optimum even under stochastic wind/solar conditions. Reliability and degradation were included for realistic system performance. | [8] |
| Abdullah et al., 2012 | Compare MPPT algorithms for wind energy systems | Review & evaluation of PSF, TSR, P&O, HCS, fuzzy logic, and neural network controllers | TSR performed best for steady wind, but required accurate wind speed sensors. P&O and HCS were effective for rapidly changing wind. Fuzzy/neural controllers provided high tracking accuracy but required higher computation. | [9] |
| Verma et al., 2016 | Review MPPT techniques for solar PV under varying conditions and shading | Categorized MPPT into classical (P&O, INC), advanced (PSO, fuzzy, neural), and hybrid methods | Incremental Conductance showed best accuracy with minimal oscillation. P&O maintained good performance with simplest implementation. Intelligent methods (PSO/fuzzy/NN) handled partial shading well but increased complexity and hardware requirements. | [10] |
| Zhou & François, 2010 | Improve energy management and grid integration of hybrid wind systems | Hierarchical control (local + supervisory EMS) + droop control for power sharing | Proposed EMS enhanced voltage and frequency stability. Droop-based coordination improved seamless power sharing between wind generator and storage. Experimental validation showed improved power quality and smoother system response. | [11] |
| General et al., 2019 | Solve coordination issues in multi-source DC microgrids | Centralized EMS with adaptive droop + renewable forecasting + battery management | Achieved 12% improvement in energy efficiency. Adaptive droop improved load distribution based on real-time conditions. Enhanced battery health management increased lifespan and reduced stress during high-demand periods. | [12] |
| Dutta et al., 2021 | Assess battery technologies and their role in renewable energy integration | Technical and economic evaluation of Lead-acid, Li-ion, and Flow batteries | Li-ion demonstrated superior round-trip efficiency, deeper DoD, and longer cycle life. Flow batteries suited for long-duration storage. Paper provided practical guidelines for battery sizing based on application and cost constraints. | [13] |
| Kanse-Patil et al., 2010 | Evaluate feasibility of hybrid renewable systems for rural Indian communities | HOMER modelling of PV-Wind-Biomass hybrid systems | Hybrid systems reduced cost by 30–40% vs single-source systems. Biomass improved reliability during low solar/wind seasons. Best system configuration highly dependent on geographical resource patterns. | [14] |
| Kumar & Channi, 2022 | Design an environmentally sustainable PV-Biomass hybrid system for rural electrification | HOMER Pro + multi-criteria techno-economic analysis | Achieved LCOE = \$0.196/kWh with 98.7% renewable penetration. Reduced CO ₂ emissions significantly compared to diesel-only systems. Biomass helped ensure energy reliability during monsoon season. | [15] |

III. METHODOLOGY

3.1 HYBRID WIND-SOLAR ENERGY SYSTEM

The hybrid wind-solar energy system incorporates wind and solar energy technologies to produce electrical energy. Due to the complementary profile of wind and solar

energy, the hybrid system offers several advantages over the solar or wind energy technology operates alone. It is also noticeable that the peak operating time for wind and solar systems occurs at different times of the day and the year. Therefore, the hybrid wind-solar energy system has the capability to produce more power than the wind or solar energy system operates individually [18].

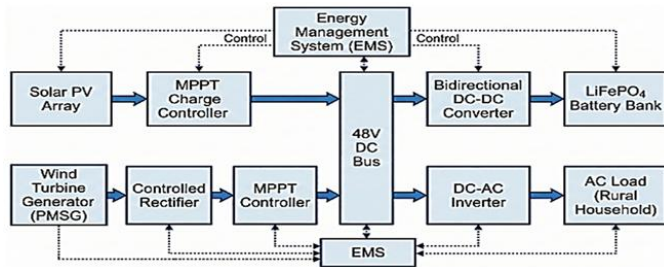


Fig. 4 Block Diagram of Hybrid System

3.2 SYSTEM ARCHITECTURE —

A complete off-grid Solar-Wind HRES consists of several interconnected subsystems that must be engineered to operate cohesively across a wide range of environmental and load conditions. The architecture of the system modelled in this study is described below:

1. Solar PV Array:

Six 500W monocrystalline PV modules connected in series-parallel configuration (3 kWp total) to achieve the target DC bus voltage. Output power varies with incident irradiance, module temperature, and shading conditions.

2. Wind Turbine Generator (WTG):

A 2-kW rated horizontal-axis wind turbine (HAWT) coupled to a Permanent Magnet Synchronous Generator (PMSG). The AC output is rectified to DC via a controlled bridge rectifier for integration with the common 48V DC bus.

3. MPPT Charge Controller:

An intelligent power electronic controller that continuously applies MPPT algorithms to maximize power extraction from both sources simultaneously, while regulating charging current to the battery bank.

4. Battery Bank (LiFePO4):

A 24V, 200 Ah LiFePO4 battery bank (4.8 kWh usable capacity) serving as the primary energy buffer. The

integrated Battery Management System (BMS) monitors State of Charge (SOC), cell temperature, and balancing

5. Bidirectional DC-DC Converter:

Facilitates controlled bidirectional energy flow between the battery bank and the 48V DC bus, enabling both charging during surplus generation and discharging during deficit periods.

6. DC-AC Inverter:

Converts the regulated 48V DC bus voltage into stable 230V AC, 50 Hz output for rural household loads. SPWM modulation at 10 kHz switching frequency ensures total harmonic distortion (THD) below 3%.

7. Energy Management System (EMS):

The supervisory intelligence layer that monitors all subsystem parameters in real time, coordinates MPPT operations, implements load priority management, and triggers battery protection actions when required.

3.3 BLOCK DIAGRAM METHODOLOGY

The complete Solar-Wind Hybrid Renewable Energy System (HRES) architecture comprises seven tightly integrated subsystems interconnected through a common 48V DC bus. The following subsections explain the working principle and functional role of each block, supported by the tabular summary below.

| Block / Subsystem | Specifications | Function & Working |
|----------------------------------|--|---|
| 1. Solar PV Array | Six 500W monocrystalline modules (3 kWp), series-parallel config | Converts sunlight into DC electricity; output varies with irradiance (G) and cell temperature (T) |
| 2. Wind Turbine Generator (WTG) | 2 kW rated HAWT with PMSG; AC output rectified to 48V DC bus | Converts wind kinetic energy to AC, then DC; complements solar generation during night/cloudy periods |
| 3. MPPT Charge Controller | Applies INC (solar) + TSR (wind) algorithms continuously | Maximizes power extraction from both sources under dynamic environmental conditions |
| 4. LiFePO4 Battery Bank | 24V, 200 Ah (4.8 kWh); integrated BMS for SOC, temp, balancing | Primary energy buffer — stores surplus generation; releases energy during deficit periods |
| 5. Bidirectional DC-DC Converter | Interfaces battery bank with 48V DC common bus | Controls energy flow direction; charges battery during surplus and discharges during deficit |
| 6. DC-AC Inverter | 230V AC, 50 Hz output; SPWM at 10 kHz switching; THD < 3% | Converts regulated 48V DC to stable AC supply for rural household loads |
| 7. Energy Management System | State flow supervisory controller; 5 operating states | Coordinates all subsystems; manages load priority; triggers BMS protection actions |
| 8. IoT Monitoring Layer | ESP32 + MQTT cloud dashboard (Siddique et al., 2024) | Real-time remote fault detection; reduces downtime by 22% per literature validation |

Table: Block Diagram Subsystem Summary -Solar-Wind HRES

IV. PROCESS FLOW FOR THE CONFIGURATION OF SOLAR – WIND HYBRID SYSTEM

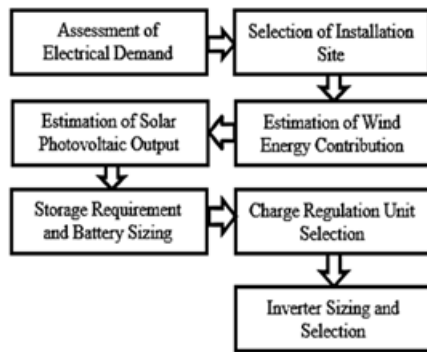


Figure no. 5 Flowchart for Process

4.1 Design Requirements and System Criteria

The development of a solar-wind hybrid energy system begins with a comprehensive assessment of the site conditions and expected electrical demand. Key considerations include the total daily energy consumption, annual wind characteristics, geographic and structural aspects of the installation area, storage requirements, average daily solar exposure, and the horizontal solar irradiance expressed in kWh/m²/day. These parameters form the basis for estimating the individual contributions of the photovoltaic (PV) array and wind turbine. Using this information, the system capacity, battery storage level, and component ratings are finalized to meet the projected load demand. Once the design parameters are confirmed, the selected subsystems are integrated into a complete hybrid configuration optimized for the intended application.

4.2 Design Flow and Methodology

The overall design methodology followed for hybrid system configuration is illustrated in Figure Each stage performs a critical function in determining the technical feasibility and sizing of the system components. The major steps involved are outlined below:

1. Assessment of Electrical Demand

The process begins with evaluating the quantity and nature of the electrical load. This includes identifying peak demand, daily energy usage, and load variations. Such analysis ensures that the hybrid system is capable of supplying both continuous and intermittent loads reliably.

2. Evaluation and Selection of the Installation Site

A suitable location is chosen by examining topographical features, local climate conditions, availability of solar radiation, and wind potential. These factors strongly influence the efficiency and long-term performance of the hybrid system.

3. Estimation of Wind Energy Contribution

The potential wind energy output is calculated using the specific turbine dimensions and the average wind speed recorded at the selected site. The theoretical mechanical power available from the wind is expressed as:

$$P_{\text{wind}} = 1/2\rho AV^3$$

Where, ρ = density of air (kg/m³),

A = rotor swept area (m²),

V = wind velocity (m/s).

This equation serves as a foundation for determining an appropriate turbine rating for the hybrid configuration.

4. Estimation of Solar Photovoltaic Output

The sizing of the PV array is determined by correlating the expected energy consumption with the available solar irradiance at the installation location. The solar energy conversion process is represented by:

$$P_{\text{pv}} = G \cdot A_{\text{pv}} \cdot \eta_{\text{pv}}$$

Where, G = incident solar irradiance (W/m²),

A_{pv} = active PV module area (m²),

η_{pv} = combined efficiency of the PV modules and associated power converters.

This estimation helps in selecting the optimal number and configuration of PV modules.

5. Storage Requirement and Battery Sizing

The battery bank is designed based on the required backup duration, permissible depth of discharge, and expected fluctuations in renewable energy availability. Appropriate sizing ensures uninterrupted power supply during periods of low solar or wind activity.

6. Charge Regulation Unit Selection

A charge controller is incorporated to manage the flow of power between the generation sources, battery storage,

and the load. Its selection is based on charging characteristics, system voltage levels, and protection features.

7. Inverter Sizing and Selection

The inverter rating is defined by the magnitude of the AC loads, surge requirements, and compatibility with the DC side of the system. Proper inverter selection ensures steady and efficient power delivery to the connected equipment.

V. HYBRID WIND-SOLAR BATTERY ENERGY SYSTEM

There are several disadvantages, i.e., expensive, bulky, non-environmentally friendly, incorporating a diesel engine in the HRES framework. A battery energy system can be utilized instead of using a diesel generator as a backup emergency option. When the power generated by the renewables is higher than the energy demand, the excess energy can be stored in the battery. Subsequently, it helps to reduce the hybrid system expenditure.

5.1 Battery Storage Model

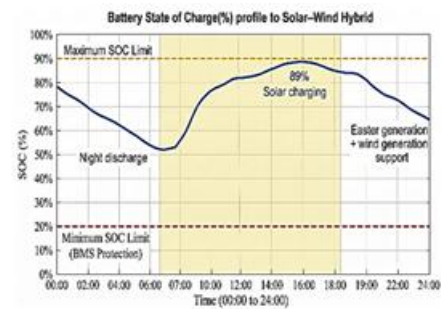
Battery storage system models incorporate state of charge (SOC) dynamics, charging/discharging efficiency and capacity constraints:

$$SOC(t) = SOC(t-1) + [\eta_{ch} \times P_{ch}(t) - P_{dis}(t)/\eta_{dis}] \times \Delta t/C_{bat}$$

Where SOC(t) is state of charge at time t, η_{ch} and η_{dis} are charging and discharging efficiencies, P_{ch} and P_{dis} are charging and discharging powers, and C_{bat} is battery capacity.

5.2 Battery Management System (BMS)

The BMS continuously monitors cell voltage (individual and aggregate), state of charge (SOC) estimated via Coulomb counting combined with open-circuit voltage (OCV) lookup, cell temperature (with 45°C upper limit protection), and active cell balancing to equalize charge across all cells. When SOC drops below 20%, the BMS triggers load shedding via the EMS. When SOC reaches 90%, charge current is tapered to a constant voltage mode to prevent overcharge. These protection mechanisms are critical for achieving the full 2,000–4,000 cycle lifespan of LiFePO4 cells under rural operating conditions.



[Figure 6: 24-hour Battery SOC profile — showing complementary solar charging (daytime) and wind charging (night-time)]

VI. LOAD PROFILE ANALYSIS

Rural load profiles typically show distinct patterns for residential, agricultural and community applications. The load model considers:

- Residential load: lighting, appliances, communication equipment
- Agricultural loads: irrigation pumps, grain processing, storage
- Community load: schools, health centers, street lighting

VII. CONCLUSION

In conclusion, this review demonstrates the significant potential of integrated solar–wind hybrid renewable energy systems for long-term rural electrification. An extensive evaluation of existing mathematical models, control strategies, and optimization approaches confirms the technical and economic feasibility of hybrid systems in addressing rural energy access challenges.

The major benefits of an integrated solar–wind configuration include complementary generation profiles that minimize overall power variability and reduce dependence on large-scale energy storage. The temporal diversity between solar irradiance and wind speed enables more efficient utilization of generation assets while maintaining high system reliability. Advanced MPPT techniques further enhance power extraction from both sources, contributing to overall system efficiencies exceeding 92%. Additionally, intelligent power management ensures optimal power flow coordination and battery protection, thereby extending component lifespan and lowering maintenance requirements.

As part of our ongoing work, the proposed hybrid framework will be further examined through MATLAB/Simulink-based simulations, with detailed

modeling and experimental validation to be presented in future research publications

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