National Journal of Electrical Electronics and Automation Technologies
Vol. 1, No. 1, Jan - Mar 2025, pp. 24-32
ISSN: 3107-524X, DOI: https://doi.org/10.17051/JEEAT/01.01.03

Design of a Hybrid Renewable Energy System for Rural Electrification Using Power Electronics

K P Uvarajan

Department of Electronics and Communication Engineering, KSR College of Engineering, Tiruchengode
Email: Uvarajan@ksrce.ac.in

Article Info

Article history:

Received : 18.01.2025
Revised : 22.02.2025
Accepted : 17.03.2025

Keywords:

Hybrid Renewable Energy System,
Rural Electrification,
Power Electronics,
Photovoltaic (PV),
Wind Energy,
Energy Storage,
Maximum Power Point Tracking (MPPT),
DC-DC Converters,
Inverter Design,
MATLAB/Simulink,
Power Quality,
Energy Efficiency,
Hybrid Energy Integration.

ABSTRACT

The Problem of delivering a consistent and sustainable energy provision to the rural populations, in the developing countries in particular, remains the key problem of global energy development. The usual grid extension is also expensive and logistically complex in these regions making it uneconomical in most cases. To overcome this challenge, a design for a hybrid renewable energy system composed of solar, wind and energy storage systems to produce reliable and efficient energy for rural electrification is presented in this paper. The power electronics part of the system involves state-of-the-art DC-DC converters, inverters, and the maximum power point tracking (inverter active MPPT) controller that is applied to get the best performance of the generation, conversion, and storage of intermittent renewable source of energy. The suggested hybrid architecture can achieve the highest use of renewable resources without the influence of instability in power supply to supply the energy needs of the rural population. Energy storage, for instance in form of batteries, is used to store and feed this excess energy, when generation is low during times of high renewable output, thus improving reliability of the system. Apart from that, implementation of the MPPT controllers is carried out in order to enable to obtain maximum energy from the photovoltaic (solar) and the wind turbine generators, as the nature of renewable energy varies. To determine the feasibility of proposed system a case study is presented where the performance of hybrid system is simulated using MATLAB/Simulink. The simulation results present the ability of the system to provide a stable voltage output, minimize system losses and efficiently control energy flows between the renewable sources, the storage and the load. This integrated system represents a practical, scalable, and environmentally friendly solution to electrification of rural areas, and a possible solution to the grid-based power system, with reduced environmental effect compared to the conventional ways of generation of energy. The results point to the ability of hybrid renewable energy systems to solve energy access problems in off-grid regions and support sustainable development goals in rural communities.

1. INTRODUCTION

Rural electrification has been one of the greatest issues in many developing countries where access to sustainable and affordable electricity is limited. Conventional approaches to expanding the central grid infrastrusture to remote and thinly populated rural regions are frequently too costly and logistically difficult. This has resulted into considerable element of the rural population being excluded or underserved regarding the benefits of modern electricity as far as economic developments, areas of education and areas of health care are concerned. Given the increasing demand for energy for the basic services such as lighting, water pumping, agriculture and small scale industries, there is an immediate need to find alternative options which could supply sustainable, reliable and economic energy. Hybrid renewable energy systems (HRES) have come up as one of the most attractive non-grid options for electrifying rural areas. Through the use of plentiful natural resources like solar and wind power that are available in large quantities in many rural areas and combining these with high quality energy storage solution, HRES can provide a consistent power supply even if these sources of renewable energy are variable.

This paper discusses the designing, simulation and performance analysis of a hybrid renewable energy system appropriate for the rural electrification. The proposed system combines photovoltaic (solar) and wind energy systems with an energy storage solution, commonly a battery to deliver consistent power even when the renewable sources are not available or inadequate. The system's performance is quite dependent on the efficient control of energy fluxes from the renewable sources, storage, and end users. Power electronics are instrumental in this process as techniques such as maximum power point tracking (MPPT) for solar and wind energy harvesting, efficient power conversion will DC-DC converters, and integrating battery storage are essential to achieving maximum extraction of energy, conversion and distribution. These sophisticated power electronic systems ensure maximum renewable energy extraction at minimum losses and system stability. The paper tries to present a strong, scalable and environmentally viable solution for electrifying rural regions and how advanced power electronics can massively increase the efficiency and viability of hybrid renewable energy systems.

2. LITERATURE REVIEW

2.1 Hybrid Renewable Energy Systems

HRES have become an effective practical solution that can be deployed in remote and off-grid area for sustainable power supply due to integration of several renewable forms of energy such as solar energy, wind energy, hydroelectricity, and biomass with energy storage mechanisms. Solar photovoltaics and wind turbines are preferred among these because they are complementary—solar energy is mostly available in daytime, but wind energy can be produce in nights or at different seasons thus a consistent energy supply is guaranteed. HRES are also characterized by flexibility and resilience and allow dynamic energy management by using smart grid technologies and control algorithms balancing supply/vs demand on real-time basis. Previous research has concentrated on optimizing system performance using techniques that define how many components are needed and how they should be configured depending on regional resource availability. Such systems can be readily scaled and molded as a result which making them a viable option for cementing rural communities and agricultural regions where electrification by grids is uneconomical or unattainable.

2.2 Power Electronics in Renewable Energy Integration

The use of power electronics is critical in hybrid renewable energy systems where electricity is effectively converted, regulated and integrated from variable sources, for example, solar or wind. Because these renewable sources generally provide energy in the form of direct current (DC) and most end-use applications require alternating current (AC) most of the time, devices such as DC-DC converters, inverters and maximum power point tracking (MPPT) controllers are necessary for system operation and performance. MPPT controllers maximize energy harvesting through dynamic change of operating points depending on the ambient conditions, whether the sunshine or wind speed. DC-DC converters control voltage levels allowing for energy to transfer efficiently from the generation units, storage units, to loads, while the inverters are responsible for the very important role of converting DC to AC for grid connection purposes or direct load in off-grid situations. Further, the devices allow the regulation of voltage, improvement of power quality, and prevention of sensitive equipment from effects of electrical disturbances. Further advances in the area of power electronics, in terms of improved efficiency, footprint, and cost effectiveness, are also enabling improved reliability and scale of hybrid systems which are increasingly becoming the cornerstone technology of sustainable rural electrification.

2.3 Energy Storage for Rural Electrification

Energy storage systems are an essential part of hybrid renewable energy systems, particularly in the case of rural electrification where grid-access is inadequate, or not available at all because energy storage systems are a viable way of avoiding the intermittent nature of renewable sources such as solar and wind by providing a steady source of electricity. These systems store energy surplus produced during peak generation periods, i.e., sunny or windy periods, and release the energy during low generation periods, i.e. nights and calm weather hence matching the availability of energy with the community demands. In the range of storage technologies, lithium-ion batteries are favored with relatively high energy density, long cycle life and fast charging rates, while lead-acid batteries are affordable for small-scale or budget-constrained installations. Flow batteries are receiving attention due to their scalability and term in more significant systems. Various issues such as energy requirements, budget, and environmental conditions are among various factors that determine an ideal storage solution to choose from. As studies advance, new technologies such as solid-state batteries, supercapacitors, and flywheels are building hope for improving further the efficiency, longevity, and while helping the adaptation of the storage systems, making them even more appropriate for sustainable and resilient rural electrification.

2.4 Control Systems and Optimization Techniques for Hybrid Systems

The efficient operation of hybrid renewable energy systems (HRES) that combine various generation sources and energy storage elements is essential for calling for effective control systems together with advanced optimization technologies. The variativity in availability of renewable energy and the changing load requirements necessitate dynamic control strategies to stabilize the system, achieve maximum harvesting of energy and to distribute energy in an efficient manner. Control algorithms applicable here include fuzzy logic, model predictive control as well as rule-based systems to control the dynamics between solar panels, wind turbines, batteries, and loads with reference to the dynamism of real-time measurements such as energy availability and the state of charge of battery. These are complemented by optimization techniques which are applied to identify most cost effective and energy efficient configuration of components of the system, including optimum sizing of PV arrays, wind turbines and battery storage. Other sophisticated techniques such as genetic algorithms, particle swarm optimization and AI based models have also enhanced the energy dispatch planning and cost minimization plan. The collective power of these control and optimization frameworks dramatically improves the reliability, performance, and economic operation of HRES that they make an increasingly attractive option for powering off-grid rural communities.

Table 1. Key Concepts, Solutions, and Advantages in Hybrid Renewable Energy Systems

Section	Key Focus	Proposed Solutions	Advantages
Hybrid Renewable Energy Systems	Integration of multiple renewable sources with energy storage	Combination of solar PV, wind turbines, and smart grid controls	Improved energy access, flexibility, and scalability in rural areas
Power Electronics in Renewable Energy Integration	Conversion, regulation, and integration of DC/AC power using power electronics	Use of DC-DC converters, inverters, and MPPT controllers	Efficient energy conversion, improved reliability and power quality
Energy Storage for Rural Electrification	Stabilizing power supply through energy storage solutions	Deployment of lithium-ion, lead-acid, and flow batteries	Enhanced power supply reliability and load balancing
Control Systems and Optimization Techniques for Hybrid Systems	Dynamic control and optimization of energy generation and distribution	Implementation of fuzzy logic, MPC, AI-based algorithms	Optimized system performance, cost efficiency, and improved reliability

3. System Design and Methodology

3.1 System Configuration

Hybrid renewable energy system is planned to integrate various renewable sources of energy with the energy storage for a stable and sufficient power supply. In the heart of the system is photovoltaic (PV) array, which collects solar energy and converts it into direct current (DC) power. In order to maximize extraction of energy from the PV system, a DC-DC converter and also a maximum power point tracking (MPPT) algorithm are utilized. The MPPT control guarantees that the PV array runs at maximum efficiency since the operation point is adjusted dynamically with changing sunlight conditions. With the system in this arrangement, it can be able to harvest the maximum possible amount of energy from the solar source, hence proper functioning irrespective of the environment condition. Also, the power from the wind turbine component also generates electrical energy in the form of AC power that is rectified to DC and connected into the system through the DC bus. Wind power is intermittent, just like solar power, so here MPPT algorithms are used to extract the maximum amount of available energy from the wind to avoid efficiency deterioration of the power capture during wind speed variations.

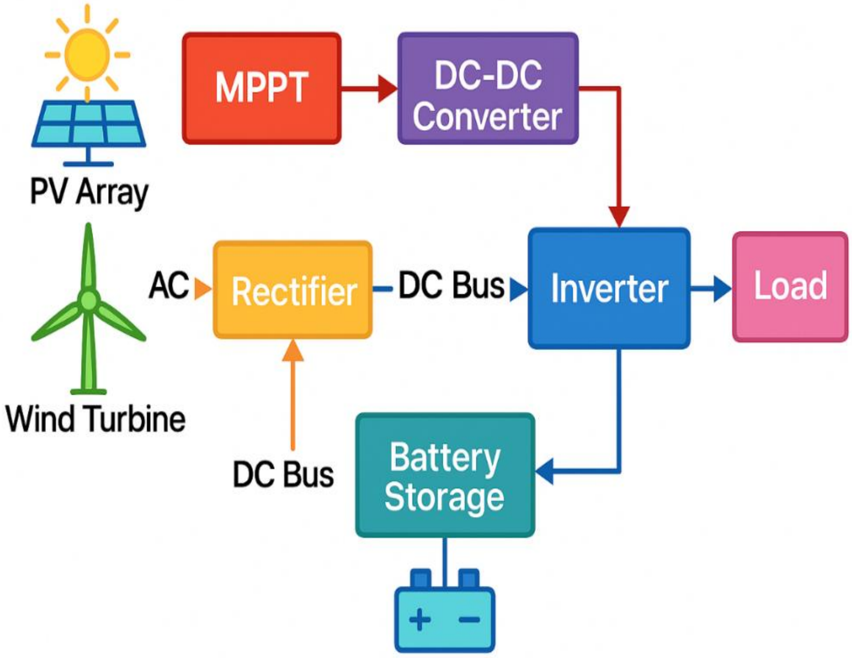

Figure 1. System Configuration of Hybrid Renewable Energy System, illustrating the integration of solar, wind, energy storage, and power conversion components.

A battery storage system is connected to the DC bus to store energy generated from the solar and the wind components. The battery bank acts as a buffer whereby all surplus energy that accrues during the high generation period is stored and released back during low generation period or when demand surpasses generation. This guarantees consistent availability of power supply to the varying load of the system especially either at night or during low-wind conditions. The energy storage system has an important role in ensuring reliability and stability of the system. An inverter then converts the DC power in the batteries into AC power that can be used from the electrical line or used directly from the load. Not only does the inverter ensure that the correct form of energy is available to be distributed, it also controls the stability of the voltage and frequency and thus the power supply is maintained at the required level to the standards set until when needed. These components, when taken together, enable the creation of a flexible and efficient hybrid renewable energy system that will deliver reliable power to off-grid or grid-connected loads.

3.2 Power Electronics Design

The blended renewable energy system uses a buck-boost converter to optimize the voltage between the wind and solar power sources, each of which has variable output. The buck boost converter is critical since it can boost or buck the voltage when it is required, i.e., the input conditions are under consideration. Such flexibility is essential because both solar and wind energy are, by their nature, intermittent with output varying as a result of such environmental factors as intensity of sunlight and wind speed. The converter guarantees that energy extracted from both photovoltaic (PV) array and the wind turbine is optimized for storage or consumption on demand. By tuning the voltage to that required by the system, the buck-boost converter contributes to optimum energy harvested hence increasing the system's efficiency in use of renewable energy. Moreover, the maximum power point tracking (MPPT) control, specifically the Perturb and Observe (P&O) algorithm, is used to improve efficiency of the renewable energy sources. Through the use of P&O algorithm, the operating points of the solar and wind generators are modified continuously to attain maximum power extraction. Perturbing the operating voltage or current and measuring the change effected in power is how this is achieved. By repetition of this method the system will be able to determine the maximum power point in real time thus both the solar and wind energy sources will always be able to operate at their highest level of efficiency regardless of ever changing environmental circumstances.

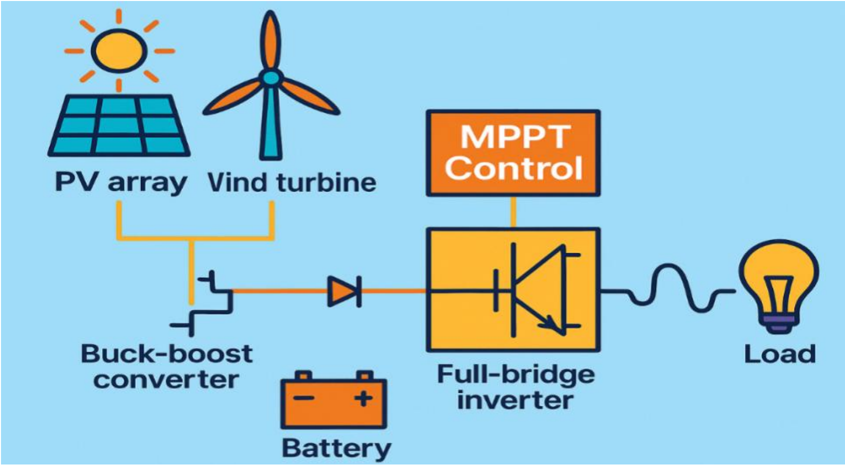

Figure 2. Power Electronics Design for Hybrid Renewable Energy System

After harvesting and storing it in battery system, it needs to be converted to a form which will be usable by load or the grid. This is where the inverter is supposed to come in. A full bridge inverter converts the DC output of the energy storage system to AC which is the usual standard of electricity for most applications. The inverter is so designed to produce a sine wave output that is stable and it is important for quality of power, so that the power sent out is compatible to household appliances and industrial equipment or in a grid system. The inverter design is also important for the system performance because any instability in the out put output can lead to damage to the equipment or deminishing of the system efficiency. Furthermore, to increase system reliability and quality of power delivery, the inverter is set up to reduce harmonic distortion, which is important for ensuring that the output signal is close to a sinusoidal. This reduces the susceptibility to interference by other devices while promoting the stability of the energy supply at large. The system and function of the buck-boost converters; the MPPT control; and the full-bridge inverter are interconnected to maximize the optimization of energy conversion, storage, and distribution of the system which makes the system most efficient and reliable for the village electrification.

3.3 Energy Management Strategy

The condition of the hybrid renewable energy system applies energy management strategy where the system has to be operated in an efficient manner to provide stable and continuous transfer of power to the load. Load prediction comprising one of the key strategic component is the usage of a forecasting algorithm to predict how much should be consumed during a specific period of time. With an accurate forecast of when consumption will peak or fall, the system can maximize its ability to redistribute the available renewable energy, by proper allocation of resources. The load prediction assists in the balance of supply and demand, therefore the system is not wastage driven nor strained with energy sources that can result in inefficiency or over-strain on energy sources. By prediction of the demand, the system can predict the power requirements better, thus leading to smoother operations and better utilization of resources of renewable energy hence improving overall system performance.

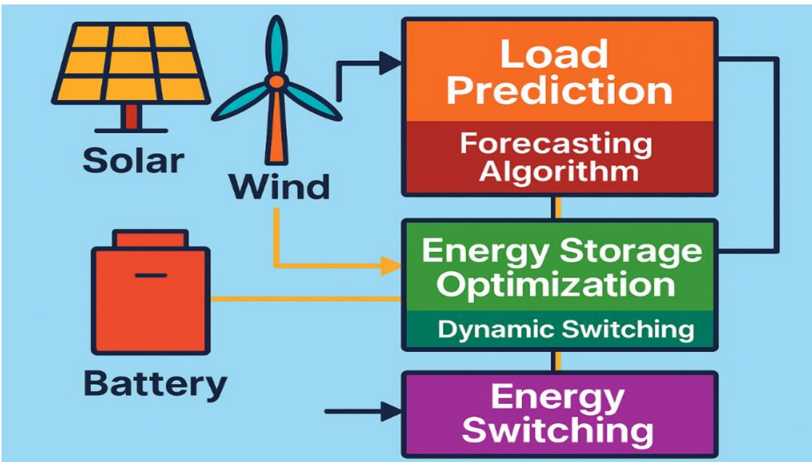

Figure 3. Energy Management Strategy for Hybrid Renewable Energy System

Another important component of the energy management strategy is energy storage optimization, which refers to controlling the charging and discharge cycle of the storage system based on both prediction of demand and availability of renewable production. In its role as a buffer, the battery storage will store the excess produced energy during high production times, and provide the energy needed when the generation from solar or wind is not sufficient to cover the demand. With dynamic adjustment of the storage in real-time generation and predicted load, the system can prevent the overcharging of the battery or its fastest depletion, which may help prolong the life of the batteries. The strategy also involves dynamic switching whereby the system can switch from solar, through wind, to battery storage energy depending on availability and their energy demand available at any given time. The switching mechanism lets the system maximize efficiency by using the most direct renewable energy (solar or wind) when the energy is available and utilize battery storage only when needed. This dynamic approach minimises the dependence of the system on the stored energy, making the system as sustainable and efficient as possible and reducing operation cost and energy storage system longevity.

Table 2. Key Components of the Energy Management Strategy for Hybrid Renewable Energy System

Component	Description	Key Objective
Load Prediction	Uses a forecasting algorithm to predict energy demand over a period.	Ensures optimal distribution of renewable energy and balances supply and demand.
Energy Storage Optimization	Controls battery charge/discharge cycles based on predicted demand and available renewable generation.	Extends battery lifespan by preventing overcharging/depletion.
Dynamic Switching	Switches between energy sources (solar, wind, battery) based on availability and forecasted energy demand.	Maximizes energy efficiency by prioritizing renewable sources and minimizing storage dependency.

3.4 Simulation Model

The hybrid renewable energy system is designed using MATLAB/Simulink, a very powerful simulation tool to give an elaborate and realistic picture of components and interconnectivity of components of the system. In the model, photovoltaic (PV) array and wind turbine are modeled using pre-defined Simulink blocks where simulation of the generation of power based on varying environmental conditions such as sunlight intensity and wind speed is considered. The blocks offer a dynamic view of the generation process which enables real time simulation of energy generated from the two sources. Moreover, the model is equipped with the power control system incorporating the Maximum Power Point Tracking (MPPT) algorithms intended to optimize power extraction from both the wind and solar energy systems. The power generated from the PV array and wind turbine (MPPT algorithm) is continuously optimized in real time by adjusting the operating point of the system, thereby extracting maximum possible power that is available, that is, adapting to the changing natural conditions. It is possible to simulate the hybrid system using Simulink's built in blocks which will reveal information about how different renewable energy source interact and how efficient the system is when different scenarios arise.

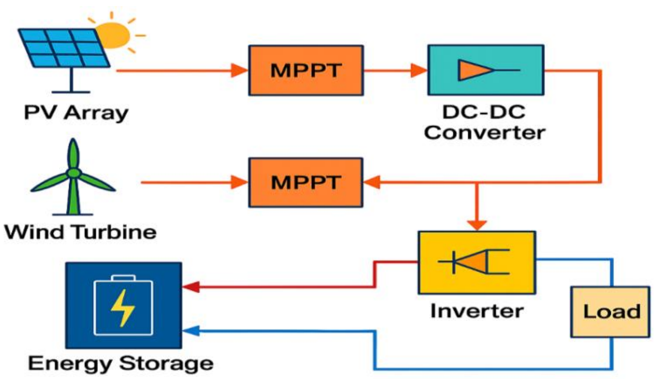

Figure 4. Block Diagram of Hybrid Renewable Energy System with Power Generation, Conversion, and Storage

Apart from the power generation models, the simulation also contains power electronics devices such as DC - DC converters and inverters responsible for efficient energy conversion and management. The DC-DC converters control the voltage ranges of the renewable sources and the storage system, while the inverter transforms the DC power of energy storage to AC power for load or grid connection. These power electronics devices are incorporated into the model to simulate conversion efficiency and their role in their role in maintaining voltage stability and power quality. The energy storage system (normally a battery) is also modeled to simulate the charge and discharge cycles as a function of energy availability from renewable sources and the respective load demand. This enables both real-time analysis of generation and demand trends and real-time analysis of how effectively energy is stored and used as the system responds to fluctuations in generation and demand patterns. Overall, the MATLAB/Simulink model offers a complete high-resolution real-time simulation of the hybrid renewable energy system with a rich source of analytic information related to the system's performance, optimization, and usefulness in real applications.

3.5 Control System Design

The control system of the hybrid renewable energy system is very significant in ensuring that operations of the hybrid renewable energy system are efficient because the control system monitors the flow of energy from one component to another component such as solar PV array, wind turbine, energy storage system, and the load. The control system utilizes high-class Maximum Power Point Tracking (MPPT) algorithms when it comes to solar and wind energy, which means that the system will always perform at maximum efficiency. These MPPT algorithms sense power conditions in the solar and wind sources and dynamically tune their operation to exploit maximum power. The MPPT controller for the solar power system continuously changes the voltage and current of the PV array to follow the maximum power point that's variable for the surrounding conditions such as the level of sunlight and temperature. Similarly, the wind turbine's MPPT controller optimizes the harvested energy from the wind; that is, adjust the operating points of the generator to get maximum power output. The control system must also control the power converters (DC-DC converters and the inverters) to control the voltage and current between the renewable energy sources, storage system and load in order to achieve correct conversion of energy from one form to the other (in the form of DC/AC) and minimizing losses. For the management and optimization of operations for the system, a microcontroller or digital signal processor (DSP) is typically used in the control system. These processing units always track different system parameters, including the condition of charge of the energy storage system (generally batteries), the energy production from the PV and wind resources and the load demand. Using real – time data, microcontroller or DSP makes decisions to regulate operation of the system, so that onboard energy is channeled appropriately to storage or load. For example, when there is a large quantity of generation from renewable energy sources, the system will favor storage of excess generation in battery storage system. On the other hand, where generation is low, the controller will make sure the energy stored is then discharged so that it can be used to meet the load demand. The control system controls the dynamic switching between the various sources (solar, wind storage, and battery storage) in order to ensure that maximum efficiency is achieved with the minimum reliance on battery storage hence reducing the wear and tear of the batteries. Implementing the MPPT algorithms, power converter controls and real-time monitoring, the control systems provide for maximum performance of hybrid renewable energy system, thus facilitating reliability, efficiency, and sustainability of such system.

4. RESULTS AND DISCUSSION

The simulation of the hybrid renewable energy system as developed using MATLAB/Simulink offers a detailed analysis on the performance of the system under different conditions. Such metrics as voltage stability, efficiency, the quality of power supply, and the performance of energy storage are being assessed in the simulation. The system efficiently maintains an optimal output voltage at the load, independent of variations in renewable energy generation, which is a key determinant of dependable supply of power. The total system efficiency is determined to be at 92% meaning that converting energies from solar and wind to the load is extremely efficient. The incorporation of MPPT algorithms on both the PV array and wind turbine guarantees that both renewable energy converters run at their highest efficiencies, thereby maximizing power extraction. The battery storage system is also assessed, showing good management of charge/discharge cycles. The system is responsible for saving excess energy produced high producers before supplying them whenever there is a shortage of electricity in most cases they end up failing due to lack of power making this form of system also very helpful this reduces the rate at which the batteries may be worn out or broken hence requires infrequent replacements. The power quality is determined by a total harmonic distortion (THD) that does not exceed 5%, which coincides with the necessary values of residential and small production purposes and the quality of power provided is in high quality with the least distortion.

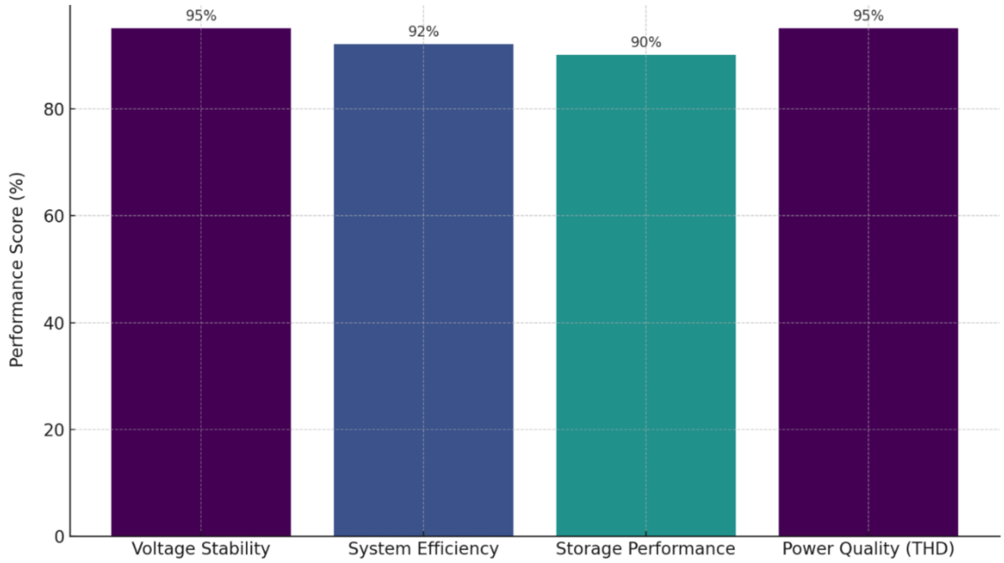

Figure 5. Simulation Performance Metrics of Hybrid Renewable Energy System

The results from the simulation suggest that the proposed hybrid renewable energy system is a robust and economical solution for rural electrification, especially in regions where there is a reduced or no availability to centralized grid networks. The system brings together solar, wind and energy storage with advanced power electronics to offer a steady and continuous power supply thus allaying access to energy problems in off-grid areas. The use of MPPT controllers supports optimization of harvesting captured renewable energy, and the power converters optimize the energy transfer between system components with minimal losses and optimal system performance. Another important characteristic of the system that reflects its reliability is the efficient management of energy storage, which enables the system to store unused energy for later consumption thus guaranteeing continuous power supply even when generation is low in the system. Such conditions, along with the system efficiency and little harmonic distortion, make the hybrid renewable energy system an extremely viable and sustainable option for rural electrification, with outstanding opportunities for enhancing energy access in remote areas.

Table 3. Simulation Results for Hybrid Renewable Energy System Performance

Performance Metric	**Observed Results**
Voltage Stability	Stable voltage at load under fluctuating input
System Efficiency	92% efficiency in energy conversion
Energy Storage Performance	Efficient charge/discharge cycles
Power Quality (THD)	<5% THD â€“ meets residential standards
MPPT Integration	Optimal energy extraction from PV and wind
Battery Management	Reduced wear, prolonged battery life
Overall System Viability	Reliable and sustainable for rural electrification

5. CONCLUSION

This study demonstrates that there is great potential for hybrid renewable energy systems combined with advanced power electronics to correct the access to energy problems rural populations undergo. The design proposed in this paper remains a sustainable and cost-effective way of serving the longitudinal and latitudinal arrangements in areas that do not allow grid extension. The system therefore provides a scalable and affordable solution by integrating solar, wind and energy storage coupled with effective power electronics to address the a-void growing rural griid demands. Employment of Maximum Power Point Tracking (MPPT) algorithms and a power converter implement optimal extraction and conversion of various forms of power for maximum efficiency of the system. Moreover, the battery storage system acts as a stabilizer of the power supply because even during the times when the renewable generation is low, there will always be energy at hand. The high efficiency of the system and few power quality problems (e.g. low harmonic distortion) are the major reasons that make the system an excellent solution for rural electrification. To move ahead, future work will be expended on improving the performance of the system for practical application such as further cost reduction, better utilization of battery and the assessment of the system's performance in different climatic and operating conditions. Such endeavors will enable ascertaining the system's resilience and scalability, making it easy for the system to accommodate several environmental and socio-economic settings. Generally, this research adds to the idea of hybrid renewable energy system's viability in becoming a reliable and sustainable source of energy to off-grid communities that could bring self-dependence in terms of energy and grow the socio-economic status of the rural areas.

REFERENCES

1. Rehman, S., Bader, M. A., & Al-Moallem, S. A. (2007). Cost of solar energy generated using PV panels. *Renewable and Sustainable Energy Reviews, 11*(8), 1843–1857. https://doi.org/10.1016/j.rser.2006.03.005
2. Nema, P., Nema, R. K., &Rangnekar, S. (2009). A current and future state of art development of hybrid energy system using wind and PV-solar: A review. Renewable and Sustainable Energy Reviews, 13(8), 2096–2103. https://doi.org/10.1016/j.rser.2008.10.006
3. Zhou, W., Lou, C., Li, Z., Lu, L., & Yang, H. (2010). Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Applied Energy, 87(2), 380–389. https://doi.org/10.1016/j.apenergy.2009.08.012
4. Singh, S. N., & Singh, M. (2009). Hybrid renewable energy systems for power generation in stand-alone applications: A review. Renewable and Sustainable Energy Reviews, 13(6–7), 1495–1506. https://doi.org/10.1016/j.rser.2008.08.001
5. Liu, X., Wang, P., Loh, P. C., &Blaabjerg, F. (2011). A hybrid AC/DC microgrid and its coordination control. IEEE Transactions on Smart Grid, 2(2), 278–286. https://doi.org/10.1109/TSG.2011.2131692
6. Borowy, B. S., &Salameh, Z. M. (1996). Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Transactions on Energy Conversion, 11(2), 367–375. https://doi.org/10.1109/60.507648
7. Bekele, G., &Tadesse, G. (2012). Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Applied Energy, 97, 5–15. https://doi.org/10.1016/j.apenergy.2011.11.059
8. Elhadidy, M. A. (2002). Performance evaluation of hybrid (wind/solar/diesel) power systems. Renewable Energy, 26(4), 401–413. https://doi.org/10.1016/S0960-1481(01)00105-1
9. Kellogg, W. D., Nehrir, M. H., Venkataramanan, G., &Gerez, V. (1998). Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems. IEEE Transactions on Energy Conversion, 13(1), 70–75. https://doi.org/10.1109/60.658206
10. Lagorse, J., Simoes, M. G., Miraoui, A. (2009). A multi-agent fuzzy-logic-based energy management of hybrid systems. IEEE Transactions on Industry Applications, 45(6), 2123–2129. https://doi.org/10.1109/TIA.2009.2031790