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Original Article

Performance Analysis of Hybrid Renewable Energy Systems for Rural Electrification

Dr. Susan Walker

Associate Professor, Massachusetts Institute of Technology, USA.

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ABSTRACT

Rural electrification remains a major challenge in developing countries, particularly in remote and economically weak regions where grid extension is difficult and expensive. Reliable electricity is essential for socio-economic growth, education, healthcare, agriculture, and industrial activities. Conventional fossil-fuel-based electrification methods suffer from high transmission losses, environmental pollution, fuel price fluctuations, and high investment costs. Hybrid Renewable Energy Systems (HRES), which combine renewable sources such as solar PV, wind, biomass, micro-hydro, and energy storage, provide an effective solution for decentralized rural electrification. These systems improve reliability by reducing the intermittency of individual renewable sources and ensuring continuous power supply through energy storage and intelligent energy management. This study evaluates different hybrid system configurations, including PV-Battery, PV-Wind-Battery, PV-Biomass-Battery, and PV-Wind-Biomass-Battery systems, based on technical, economic, environmental, and reliability factors. Key performance indicators such as renewable energy fraction, levelized cost of energy, net present cost, system efficiency, and carbon emission reduction are analyzed. The results show that multi-source hybrid systems can achieve more than 90% renewable energy penetration while providing reliable and cost-effective electricity. Biomass backup generation further improves power availability and reduces storage requirements. Economic analysis indicates a 20–35% reduction in electricity costs compared to diesel-based systems, along with significant reductions in greenhouse gas emissions. Overall, the study confirms that Hybrid Renewable Energy Systems are technically feasible, economically viable, and environmentally sustainable solutions for rural electrification, supporting universal energy access and sustainable development.

KEYWORDS

Hybrid Renewable Energy Systems, Rural Electrification, Solar Photovoltaic Systems, Wind Energy Conversion Systems, Biomass Energy, Energy Storage Systems, Distributed Generation, Microgrids, Renewable Energy Optimization, Sustainable Energy Development.

1. INTRODUCTION

1.1. Background

There is no denying that the availability of reliable electricity is one of the most essential requirements for economic development, social progress and living standards improvement. Electricity is vital to many critical services including education, healthcare, communication, transportation, water systems and agriculture which are important in helping to reduce poverty and develop communities. Although significant investment has been made in power infrastructure across numerous countries, many people in remote areas, especially in developing countries, still suffer from inadequate access to electricity or from unstable, weak or unreliable supplies. Poor electricity access constrains learning, health services, productivity of agriculture and economic development. The traditional methods used to provide electricity to rural communities have been to extend the centralized utility. In not so densely populated and remote areas, however, such a solution is often not economically viable because of high installation costs, large transmission power loss and large transmission infrastructure requirements. Meanwhile, the world is facing the challenges of the growing scarcity of fossil fuels, rising energy prices, greenhouse gas emissions, and environmental damage, which has driven an increasing shift to sustainable energy solutions. These renewable energy sources, including small hydropower, biomass, solar and wind energy offer the potential for environmentally friendly energy generation, are abundant and can be developed in many rural areas without significant impacts on food or water security, making them good options for decentralised energy generation. However, the availability of some renewable energy sources is not guaranteed, such as intermittent wind and solar power. In order to overcome these challenges, Hybrid Renewable Energy Systems (HRES) have been designed to incorporate various renewable energy sources along with energy storage solutions and intelligent control systems. Hybrid renewable systems can combine different renewable energy sources to achieve stable and uninterrupted electricity supply, reducing reliance on traditional generators that rely on fossil fuels. Thus, HRES have become a very efficient and viable approach to rural electrification and have played an important role in providing energy access, environmental protection and long-term socio-economic development in rural areas of the world.

1.2. Importance of Performance Analysis of Hybrid Renewable Energy Systems

The ability to analyze the performance is an integral part of the design and implementation of a Hybrid Renewable Energy System (HRES), as it allows researchers, engineers, and policymakers to evaluate the technical, economic, and environmental effectiveness of different configurations. A full performance analysis can be used to determine the best mix of renewables, storage technologies, and control to ensure reliable and sustainable electricity generation. Systematic analysis can be used to identify potential operational problems which can be resolved prior to large scale deployment, thereby increasing the efficiency of the system and minimizing overall project risks. The relevance of the performance analysis can be seen in the following points.

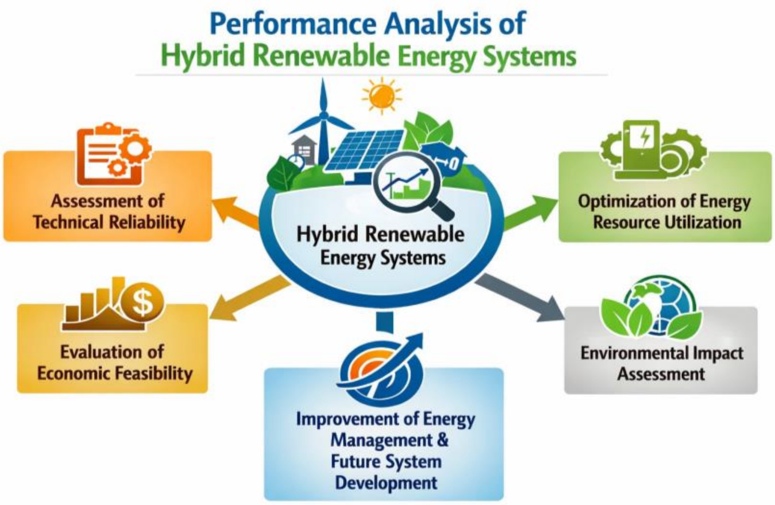

Fig 1 - Importance of Performance Analysis of Hybrid Renewable Energy Systems

1.2.1. Assessment of Technical Reliability

The main goal of performance analysis is to assure the technical reliability of hybrid renewable energy systems. Solar and wind power are renewable resources, which are subject to the vagaries of nature. Performance assessment allows for the determination of whether the system can comply with the electricity demand under various weather patterns, seasonal changes and load conditions. Measuring the consistency of electricity supply is done using reliability indicators, including Loss of Power Supply Probability (LPSP), energy availability and system uptime. The detailed reliability analysis ensures the uninterrupted power supply for residential, commercial, agricultural and community use, especially in remote locations where power interruptions can have a substantial social and economic impact.

1.2.2. Optimization of Energy Resource Utilization

Performance analysis is a critical aspect in optimal utilization of available renewable sources of energy. A study of the energy contribution of solar photovoltaics, wind, biomass and storage can help researchers determine the most efficient operating strategies. Analysis can minimize energy loss, optimize renewable energy and maximize energy use from locally available resources. It also can enable optimal sizing of components, to ensure that generation and storage capacities are not over or under sized. Optimizing how resources are used helps to optimize the overall performance of the system and reduce operational costs and environmental impacts.

1.2.3. Evaluation of Economic Feasibility

Project implementation and sustainability depend on the economic viability of a hybrid renewable energy system, which is a significant factor determining project implementation. Performance analysis delivers detailed data on capital investment, operation and maintenance costs, fuel costs, component replacement costs and lifecycle costs. Financing feasibility is assessed through the use of various economic indicators, including Net Present Cost (NPC), Levelized Cost of Energy (LCOE), payback period, and return on investment. Such analyses can assist investors, utilities and

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government agencies in choosing the most cost-effective energy solution to provide reliable electricity at affordable costs while ensuring an acceptable economic return along the project's life cycle.

1.2.4. Environmental Impact Assessment

A key part of performance analysis is also the assessment of the environmental benefits related to hybrid renewable energy systems. Fossil fuel dependence is greatly decreased by the use of renewable energy technologies and they have a positive impact on the reduction of greenhouse gas emissions. The environmental performance assessment enables the researchers to measure the reductions in carbon dioxide emissions, fuel consumption, air pollution and ecological effects vs. conventional power generation systems using diesels. It helps to sustain energy planning and helps government to achieve climate change reduction targets, environmental laws and regulations and sustainable development agendas, and to encourage cleaner energy production methods.

1.2.5. Improvement of Energy Management and Future System Development

Analysis of performance is useful for designing advanced energy management strategies and the next generation of hybrid system design. Operational data, power flow characteristics, storage behavior, and load demand pattern can be analyzed to formulate intelligent control algorithms that can optimise the operation of the system in real time. The results further indicate that the adoption of new technologies such as artificial intelligence, machine learning, smart grids, Internet of Things (IoT) monitoring systems, and evolved battery storage solutions is supported. The continuous performance evaluation helps in updating and upgrading the system, provides more flexibility in operations, makes the system more resilient to uncertainties and supports sustainable operation of hybrid renewable energy systems in the rural electrification and decentralized energy sector.

1.3. Challenges in Rural Electrification

Rural electrification is an important element of socio-economic development, enhancing the quality of living and enabling the provision of basic services like education, health, agriculture and communication in rural areas. There are however, some technical, economic and operational issues that prevent the implementation of reliable electricity infrastructure in the rural areas. Many rural communities are situated in remote, challenging-to-reach areas that are poorly connected to other areas, making geographic isolation one of the largest barriers. Lack of adequate roads and logistics further adds cost of moving equipment, construction material and maintenance staff which makes electrification projects more expensive and time consuming. The other significant problem is load variability, which refers to the significantly different electricity demand throughout the day and from one season to the next. Household consumption, irrigation for agricultural uses, small scale industrial processes and community services impose different loads, making it difficult to plan the systems and size the capacity. Further, fluctuating energy resources is a major challenge to electrification systems using renewables. Solar PV generation is influenced by the availability of sunlight and so is variable depending on cloud cover and seasonal variations, and wind power generation is variable depending on the wind conditions in the area. These variations result in power supply irregularities, and

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effective energy storage systems or backup generation sources are needed to achieve power supply reliability. Another significant challenge for rural electrification programs is lack of finances. While there are long-term cost savings with renewable energy systems, the upfront investment cost can be quite high. Project implementation may be postponed or even impossible because of limited financial resources, poor access to credit facilities, and budget constraints, especially in developing areas. Moreover, operating and maintenance problems can impact the sustainability of rural energy systems. Few remote communities have access to skilled technicians, spare parts and technical support services. This, in turn, could lead to prolonged periods of equipment failures, impacting system reliability and user confidence. To overcome these challenges, the role of comprehensive planning, technology selection, capacity building programmes, supportive government policies, and innovative ways of financing are essential. The successful implementation of these initiatives can help overcome these challenges and ensure that rural areas have access to reliable, affordable, and sustainable electricity services, which can have a significant impact on economic growth, social development, and the quality of life in rural communities.

2. *LITERATURE SURVEY*

2.1. Evolution of Hybrid Renewable Energy Systems

Hybrid Renewable Energy Systems (HRES) have emerged to meet the need for secure, sustainable, and cost-effective power generation supplies, especially in rural and remote areas where grid extension is not economic. In the early stages of the rural electrification programme, the use of diesel generators was popular because of their ease of installation, operational flexibility and capacity to supply continuous electricity service. However, with fuel and transport costs becoming more expensive in distant areas, and the cost of diesel generation causing greater environmental concerns around emissions of greenhouse gases, the drawbacks of using diesel were identified. Researchers thus started investigating alternative sources of renewable energy, in particular solar PV systems, which provided clean and abundant energy resources in many developing nations. Research during the period 2000-2015 indicated that PV systems used independently could cut the operational costs and also carbon emissions considerably, and supply reliable electricity in the areas of high solar irradiance. However, solar energy is not continuous and required huge battery bank to ensure supply during the night and cloudy days, which adds to the cost of the system. To alleviate these constraints, researchers have proposed hybrid combinations of renewable energy resources, including solar, wind, and biomass. These systems benefited from the complementary nature of the resources used, leading to greater reliability, more available energy and decreased reliance on energy storage systems. Consequently, hybrid renewable energy systems, a combination of different energy sources, became a promising approach to sustainable rural electrification for the world.

2.2. Solar-Wind Hybrid Energy Systems

The utilization of complementary renewable sources and the enhancement of the overall reliability of the power generation has drawn a lot of attention on solar-wind hybrid energy systems. Solar energy is generally more available in the day time while wind energy is generally more available during the night time or seasons when solar radiation is low. Complementary behavior

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allows hybrid systems to supply a balanced and consistent power supply, while still using standalone renewable technologies. Many studies have examined PV-WB systems and their techno-economic performance, and they have shown substantial gains in the use of renewable energy. For instance, Yang et al. found that PV and wind generation, combined with battery storage, significantly improved the reliability of the energy system and minimized energy shortages. Likewise, Nema et al. showed that the solar and wind resources could be combined, which reduced the amount of battery storage needed due to the correlation between the two resources. Dalton et al. said systems of wind and PV can yield lower energy production cost as a consequence of better resource utilization and optimization of component sizing. Moreover, Khan and Iqbal pointed out that hybrid microgrids with solar and wind power resulted in improved voltage regulation, frequency stability, and overall power quality. All of these investigations have found that hybrid systems incorporating solar power can not only improve the integration of renewables, but also lower battery cycling rates, lengthen battery life, lower operating costs, and improve long-term system sustainability.

2.3. Biomass-Based Hybrid Systems

Biomass-based hybrid energy systems are a significant step towards renewable energy integration, as biomass can generate electricity on demand and with control that is not dependent on weather conditions. Biomass energy is a renewable energy source, unlike solar and wind energy which is intermittent in nature, biomass can be produced on a continuous basis in the rural areas by utilization of agricultural residues, forestry residues, animal manure, etc. which are available throughout the year. However, integrating biomass generators into hybrid renewable systems can enhance the reliability of the system, generating electricity during times of low solar radiation and weak wind speeds. Besides, biomass utilization helps in good waste management, helps to avoid open field burning, and offers economic benefits due to the creation of jobs in the local community and gathering of resources for biomass generation. Several studies have shown that hybrid systems with biomass generators will have a smaller battery storage size and energy interruption are reduced as compared to solar or wind-powered systems. It has also been noted that biomass-based microgrids can allow for reliable power generation and the ability to provide critical loads like agricultural processing facilities, educational institutions, and healthcare facilities. As a result, biomass integration not only improves the technical performance, economic feasibility and the social impacts of hybrid renewable energy systems but is also especially applicable to the rural electrification projects in agricultural areas.

2.4. Research Gaps and Future Directions

Although hybrid renewable energy system development has made substantial advances, there are still research gaps that need to be addressed and continue to be the focus of study. However, forecast errors in the renewable energy resources, such as variations in solar irradiance, wind speed, and biomass availability, are one of the key challenges faced, as it directly impacts system performance and operational planning. Traditional forecasting methods may not effectively address the complexity of environmental uncertainty, resulting in suboptimal energy management decisions. One of the other big hurdles is the creation of more sophisticated energy management

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algorithms to seamlessly integrate multiple generation sources, storage systems, and energy demands in real time. The battery degradation modeling is still a research topic as storage systems degrades over time and affects not only economic, but also technical aspects. Moreover, numerous economic assessments have not fully considered uncertainties that arise with equipment costs, fuel prices, maintenance costs, and policy incentives. Renewable energy projects require a certain level of social acceptance, community involvement and stakeholder engagement that, if not considered, can be overlooked. In conclusion, future studies should aim to implement A.I.-, machine learning-, and predictive-based hybrid energy management systems and encourage the use of smart microgrids, Internet of Things (IoT)-based monitoring systems, and adaptive control strategies. These will be expected to lead to better efficiencies, reliability, resilience and sustainability of the system and to speed up the deployment of hybrid renewable energy systems for rural electrification across the world

3. METHODOLOGY

3.1. System Configuration and Resource Assessment

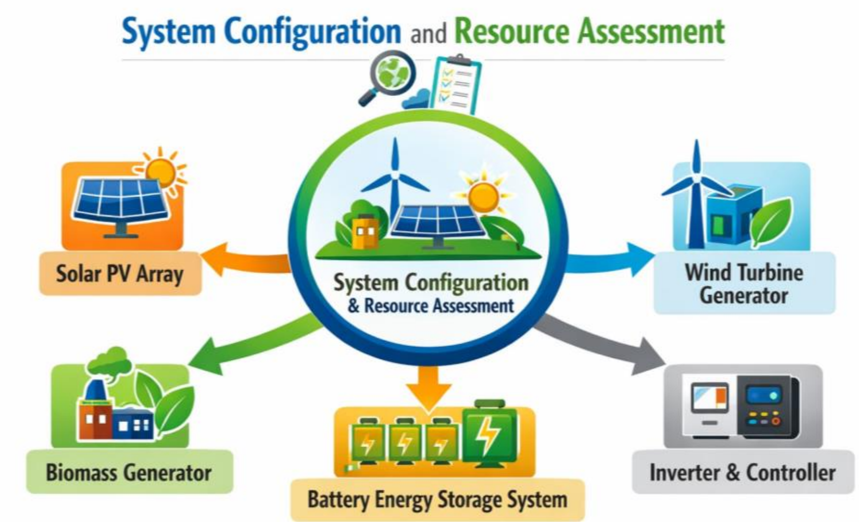

Fig 2 - System Configuration and Resource Assessment

3.1.1. Solar PV Array

The solar PV array is the major renewable energy generating equipment of the proposed hybrid renewable energy system. It is based on the photovoltaic effect of semiconductor-based solar cells, which directly convert the sun's energy into electrical energy. The PV array output power is influenced by solar insolation, ambient temperature, PV panel orientation and system efficiency. PV systems can be a cost-effective and environmentally friendly source of electricity with low maintenance requirements especially in areas with high solar radiation. The solar array provides power to the loads and charges the battery energy storage system during the day, if there is solar energy available. Solar PV can be a major contributor of reduced reliance on conventional fossil fuel-based generation and reduced greenhouse gas emissions.

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3.1.2. Wind Turbine Generator

Wind turbine generator helps in generating wind power, which helps in complementing the solar power generation. The availability of wind power is not always in line with that of solar energy, so wind power is valuable to incorporate in hybrid renewable power systems. Wind turbines can produce electricity when there is not a lot of sunlight as is the case at night and in the cloudy season. Wind speed, turbine design, rotor diameter, hub height and local climatic conditions are all factors affecting the performance of a wind turbine. The Hybrid system can be designed to ensure more consistent and reliable power production over the course of the year due to the complementary nature of Solar and Wind resources. Additionally, the compatibility of wind energy with the existing network decreases the reliance on battery storage systems and boosts the energy supply network efficiency.

3.1.3. Biomass Generator

The biomass generator acts as a dispatchable renewable energy which can provide continuous power generation and control. It uses organic sources like agricultural residues, forestry waste, crop by-products and animal wastes as fuels for the generation of electricity. Unlike solar and wind energy, biomass energy generation is not weather dependent and can provide energy when a low renewable resource availability occurs. The biomass generator also increases system reliability by providing an alternate source of biomass during extended periods of cloudy or low wind. Apart from its contribution towards energy security, use of biomass provides local employment opportunities, helps in handling waste sustainably, and averts environmental pollution. In terms of technical and economic viability of rural electrification projects, biomass integration plays a supporting role.

3.1.4. Battery Energy Storage System

Battery Energy Storage System (BESS) is an important element for ensuring stability and reliability of hybrid renewable energy system. It delivers stored electricity from solar PV panels and wind turbines during times of low demand, when they are producing excess electricity, or during times of high demand when generation is low. The battery system can be used to store energy when production from renewables is not consistent, providing a steady power supply to consumers. The storage capacity, charging and discharging efficiency of batteries, depth of discharge, cycle life and temperature conditions are all key factors to consider when looking at battery performance. The BESS can effectively regulate energy storage and release, improve the utilization of renewable energy, and reduce the energy shortage phenomenon of remote and off-grid applications, thereby enhancing the power quality.

3.1.5. Inverter and Controller

The proposed hybrid renewable energy system is based on inverter-controller as the central power management unit. The inverter converts the direct current (DC) electricity produced by the solar cells and stored in batteries into alternating current (AC) electricity that can be used by the household, commercial and industrial loads. The controller also keeps a check on the behavior of the system and controls the power distribution between the renewable energy sources, battery storage

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system, biomass power generator and connected loads. Advanced control algorithms enable these renewable resources to be used optimally and to keep the system components from being overcharged, over-discharged, experiencing voltage fluctuations, and from being overloaded. This synchronized control of the inverter and controller provides better overall efficiency, reliability and flexibility of operation, which allows seamless integration of multiple energy sources into the hybrid power generation system.

3.2. Mathematical Modeling

The development and testing of hybrid renewable energy systems require mathematical modeling as one of the key steps as it offers a quantitative assessment of the power generation capacity of various energy sources in different operating conditions. In the suggested hybrid system, mathematical models are developed for the solar PV array, wind turbine generator and biomass generator to predict the energy output of these individual generators and evaluate their contribution to the performance of the system. The amount of power produced by the Solar PV system depends on the efficiency of the PV modules, the total area of the PV panels installed and the amount of solar irradiance received from the sun. Overall, PV arrays generate more electricity when the amount of sunlight hitting them is greater, and the more area of the PV panel is in direct sunlight. The PV module's conversion efficiency is a measure of the number of solar cells' efficiency to convert the solar energy incident to electrical energy. This means that the more efficient panels and more solar irradiance means more electricity produced. Other non-environmental factors like temperature, dust accumulation, shading effects and PV panel orientation may also affect the effective PV system performance. The power generation of the wind turbine generator is mainly influenced by air density, rotor swept area, wind speed, turbine power coefficient. Air density is the amount of air available to extract energy from the air, and the rotor swept area is the area of a circle swept by the rotating turbine blades. As wind power is proportional to wind velocity raised to the third power, wind velocity is the most important factor that affects turbine performance. As a result, even a slight boost in wind speed can drastically improve electricity production. The power coefficient is a measure of how efficiently the wind turbine transforms the wind's kinetic energy into mechanical energy, and then into electrical energy. The electrical power generation of the biomass generator is determined by the efficiency of biomass conversion system, calorific value of biomass fuel and biomass mass flow rate fed to the biomass generator. Calorific value is the amount of energy liberated during combustion of unit quantity of biomass while mass flow rate is the quantity of biomass burnt per unit time. The higher the quality of the fuel and the more energy available, the more energy is produced. The generation of biomass does not depend on the weather conditions and hence it is a reliable, dispatchable energy source which complements the intermittent solar and wind power in the hybrid renewable energy system. These mathematical models are combined to create a basis for system sizing, optimization, performance analysis, and energy management analysis. The amount of electric power produced by a biomass generator is related to the biomass mass flow rate fed to the generator, the calorific value of the biomass fuel and the conversion efficiency of the biomass conversion system. The calorific value is energy released by unit quantity of biomass during combustion while the mass flow rate is the quantity of biomass consumed per unit time. The higher

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the fuel quality the higher the energy production, and the more biomass available, the more energy can be produced. Because the biomass generation is not dependent on weather conditions, it is a reliable and dispatchable power source that is complementary with intermittent solar and wind power sources in the hybrid renewable energy system. These mathematical models are combined to form the basis of system sizing, optimization, performance analysis and energy management analysis.

3.3. Optimization and Energy Management

Fig 3 - Optimization and Energy Management

3.3.1. Minimum Net Present Cost (NPC)

One of the main goals during optimization of hybrid renewable energy systems is to minimize the Net Present Cost (NPC). The total life cost of the system (NPC) is the sum of capital investment, installation cost, operation and maintenance cost, component replacement cost, fuel cost and salvage value at the end of the project life. Reducing NPC allows designers to determine the most cost effective mix of solar panels, wind generators, biomass generators, batteries and power electronics for a given set of performance parameters. A lower NPC means that the project is economically more viable, in terms of financial returns for operators and consumers and is more attractive for sustainable development and rural electrification applications. Maximum Renewable Fraction (RF)One of the key economic metrics for assessing the average cost of producing one unit of electricity over the lifetime of the hybrid energy system is the Levelized Cost of Energy (LCOE). It takes into account all project costs such as capital investment, maintenance costs, fuel costs, replacement costs etc., and then divides them by the electricity produced over the life of the project. The goal of minimizing the LCOE is to generate electricity at the lowest cost, while maintaining system efficiency and reliability. The lower LCOE makes electricity more affordable for consumers and makes renewable energy technologies more competitive than fossil fuel based power generation systems.

3.3.2. Maximum Renewable Fraction (RF)

Renewable Fraction (RF) is the ratio of total energy demand met by renewable energy like solar, wind and biomass in hybrid system. Increasing the renewable fraction is an important goal

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since it decreases reliance on non-renewable energy sources and mitigates environmental effects from fossil fuel usage. A higher renewable fraction reflects higher use of clean energy resources which result in reduced GHG emissions, increased energy sustainability, and increased energy security. The aim of optimization techniques is to reduce the share of renewable energy and ensure economic viability and stability. For rural and remote communities, where sustainable and environmentally-friendly energy solutions are of paramount importance, achieving a high renewable fraction is especially crucial.

3.3.3. Maximum Reliability

Reliability is one of the important performance criteria that indicates the capacity of the hybrid renewable energy system to provide electrical energy demand at all times under different operating conditions. The aim for maximising reliability is to minimise power outages, unmet load demand and a stable electricity supply year round. Factors that affect reliability include renewable resource availability, battery storage, backup generation and energy management strategy effectiveness. Hybrid systems are able to integrate various energy sources and energy storage technologies, which leads to a higher system resilience in case of fluctuations in individual renewable energy sources. High reliability systems improve consumer satisfaction, help critical infrastructure operate and and provide reliable power for residential, commercial and agricultural uses.

3.4. Performance Evaluation Metrics

Performance evaluation indicators are important to understand the technical, economic and environmental efficiency and effectiveness of hybrid renewable energy systems. These indicators are used to compare various configurations of the system and to decide on the best possible design for an application in a rural electrification situation. The Levelized Cost of Energy (LCOE) is one of the most significant metrics, denoting the average cost of electricity generation throughout the system's lifespan. It includes fuel costs, capital investment, operation and maintenance costs, replacement costs, etc., giving a standardized estimation of the energy production cost. The lower the LCOE, the more economically competitive and affordable the energy system will be. The other important indicator is Net Present Cost (NPC), which is the total present value of capital costs involved in installation, operation and maintenance, component replacement and disposal costs of the hybrid system. The use of NPC allows for long-term financial assessment and determination of the best system configuration. The Renewable Fraction (RF) is also commonly used to quantify the percentage of energy coming from renewable energy sources like solar, wind and biomass. The renewable fraction is a higher value, meaning that more of the energy resources are being used that are clean, and less that are derived from fossil fuels, thus improving the environmental sustainability. Electricity supply reliability can be measured with many indicators; Loss of Power Supply Probability (LPSP) is one such indicator that quantifies the probability of the system failing to supply electricity during a given period. Lower LPSP ratings indicate increased system reliability and improved system quality of service for consumers. Carbon dioxide (CO_2) reduction is determined by how much GHG emissions are reduced by using renewable energy technologies instead of conventional fossil-fuel electricity generation. The more CO_2 reduced, the better for the environment

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and the more for climate change mitigation. Lastly, system efficiency is related to how effectively the hybrid energy system utilises the available renewable resources to generate the required electrical energy. It shows the performance of a combination of generation units, storage units, power converters, and control. The higher the efficiency levels, the better the energy is being used, that there are less losses, and the better the performance of the system. The comprehensive nature of the combined evaluation metrics allows researchers and system designers to create and optimize hybrid renewable energy systems for long-term rural electrification and sustainable energy development.

4. RESULT AND DISCUSSION

4.1. Comparative Performance Analysis

The comparative technical performance, economic and environmental analysis of the proposed hybrid renewable energy system indicates significant benefits over the conventional diesel based power generation system. The simulations show that the combination of different renewable energy technologies, such as solar PV, wind, biomass and battery storage, allows for the more efficient use of local energy resources and decreases reliance on traditional and fossil fuels. The most important result is increased renewable energy penetration (high percentage of RE power in the total electricity demand). This boost in renewable energy input not only improves energy security but also lowers its reliance on volatile fuel prices and supply chain disruptions that are common for diesel-powered systems. The significant decrease in fuel reliance is another noteworthy aspect. The traditional diesel generators need to have fuel supply, transportation and storage, which leads to high operational expenses, especially in the remote and rural areas. Hybrid renewable systems, on the contrary, exploit solar radiation, wind power and biomass resources locally available and free of charge, thus decreasing the amount of fuel to be used and the fuel expenses linked to it. Combining several generation technologies also helps to increase system reliability. The intermittent nature of some renewable resources means that a lack in one resource can be offset by the generation of another resource or energy stored in batteries. The coordinated operation provides a more stable and continuous electricity supply and reduces the probability of loss of electricity supply. In an economic sense, simulation results show that the hybrid renewable systems have lower LCOs although they have higher upfront costs. These all result in substantial cost savings over the equipment's life cycle, including fuel savings and reduced maintenance. Moreover, a significant reduction of GHG emissions, especially $CO2$ emissions, has been revealed by environmental analysis when compared to diesel-only systems. Transitioning away from fossil-fuel generation toward clean generation technologies will reduce the climate change impacts and contribute to sustainable development goals. The comparative analysis overall validates that hybrid renewable energy systems offer an improved solution for rural electrification in that they are capable of delivering clean, reliable and cost effective generation, in addition to their ability to support long-term energy sustainability and energy resilience, and that they also have the ability to deliver low carbon energy generation.

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4.2. Performance Comparison of Different HRES Configurations

Table 1: Performance Comparison of Different HRES Configurations

Performance Parameter (%)	PV-Battery	PV-Wind-Battery	PV-Biomass-Battery	PV-Wind-Biomass-Battery
Renewable Energy Fraction	82	89	91	96
System Reliability	93	96	98	99
Energy Availability	92	95	98	99
Fuel Consumption Reduction	70	82	90	98
CO_2 Emission Reduction	75	87	92	98
Overall Efficiency	78	84	88	92
Economic Savings	65	72	81	89
Battery Utilization Efficiency	74	81	85	90

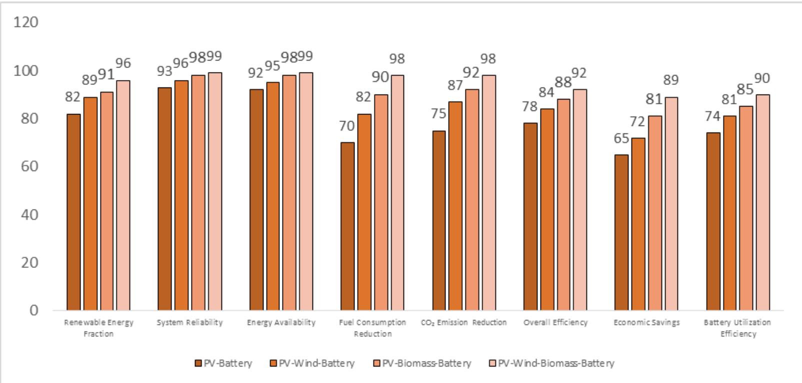

Fig 4 - Performance Comparison of Different HRES Configurations

4.2.1. Renewable Energy Fraction

Renewable Energy Fraction (REF): It represents the proportion of electricity demand being met by renewable energy sources in a hybrid renewable energy system. The PV-Battery system was found to have a renewable fraction of 82%, with a PV-Wind-Battery system being 89% when the complementary use of solar and wind resources was accounted for. The PV-Biomass-Battery combination also increased the share of renewable energy generation to 91%, as biomass-based generation is always available. The PV-Wind-Biomass-Battery combination had a highest renewable fraction of 96%, showing that using several renewable energy sources together achieves the highest use of clean energy and limits the dependence on conventional backup generating power.

4.2.2. System Reliability

Reliability of the hybrid energy system is the characteristic of reliably meeting electricity demand without disruptions over time. PV-Battery configuration had a reliability rating of 93%, meaning that it experienced periods of energy deficit or shortage. The PV-Wind-Battery system also used wind generation to enhance system reliability by adding power sources when the sun was not shining, to 96%. Biomass generators were also used with PV to make the PV-Biomass-Battery

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configuration 98% reliable since biomass generators would supply dispatchable energy, without regard to weather conditions. By coordination, multiple generation resources and energy storage were achieved the highest reliability of 99%, and the power supply was almost unaffected.

4.2.3. Energy Availability

The Energy Availability is the percentage of the time that sufficient electrical energy is available to satisfy the power needs of consumers. PV-Battery energy availability was limited to 92% due to intermittency of the solar PV system and battery storage constraints. In the PV-Wind-Battery configuration, the availability reached 95% with the introduction of wind generation. PV-BB system was 98% availability as biomass generation is very reliable. The system with PV-Wind-Biomass-Battery showed the highest energy availability (99%), which demonstrates the advantages of multiple renewable energy sources in order to provide continuous energy power supply under different environmental conditions.

4.2.4. Fuel Consumption Reduction

Fuel consumption reduction is the reduction in conventional fuel consumption as a result of integrating renewable energy. The PV-Battery configuration resulted in a 70% reduction in fuel consumption from the traditional diesel system. By adding wind energy, the PV-Wind-Battery system achieved an 82% reduction in fuel consumption due to the additional renewable electricity it generated. The PV-BB system showed a reduction of 90 % because the renewable biomass fuel was used and fossil fuels were not as much used as in the other systems. The PV-Wind-Biomass-Battery system provided the best initial fuel consumption reduction (98%) which shows that the electricity generation using conventional fuel could be replaced nearly completely.

4.2.5. CO_2 Emission Reduction

One of the important environmental performance indicators is the reduction in carbon dioxide emissions which indicates the effectiveness of renewable energy technologies in reducing CO2 emission. Solar energy was used to achieve a 75% reduction in CO_2 emissions in the PV-Battery system. Utilization of wind power generation further reduced emission to 87% in the PV-Wind-Battery configuration. The PV-Biomass-Battery system was able to reduce by 92% due to the low dependency on fossil fuels and the renewable character of biomass fuel. PV-Wind-Biomass-Battery achieved the highest environmental benefit, reducing carbon emissions by 98%, showing its vital role in sustainable and low-carbon energy development.

4.2.6. Overall Efficiency

Overall system efficiency is a measure of the efficiency of the use of available renewable resources to produce useful electrical energy. Solar conversion efficiency and battery losses were the dominant factors for the PV-Battery system and resulted in an efficiency of 78%. Adding wind energy, which increased energy generation diversity and utilization of energy resources, further increased efficiency to 84%. PV-BB system configuration achieved high efficiency of 88% with continuous operation of biomass generation systems. The PV-Wind-Biomass-Battery system, which integrated all the above renewable technologies, recorded the highest overall efficiency of 92%, demonstrating the benefits of using complementary renewable technologies to optimize the efficiency of the energy system and to reduce the losses.

4.2.7. Economic Savings

Economic savings are the savings in total energy production cost from the conventional fossil-fuel-based power system. Fuel and maintenance costs resulted in an economic savings of 65% in the PV-Battery configuration. This PV-Wind-Battery system reduced the dependency on batteries and increased renewable energy generation to 72% while improving cost savings. The PV-Biomass-Battery option resulted in 81% savings, because of the better system reliability and fuel cost reduction. The PV-Wind-Biomass-Battery configuration achieved the highest economic benefit, with savings reaching 89% and the configuration was economically attractive over the long term, although it has higher installation costs.

4.2.8. Battery Utilization Efficiency

Battery utilization efficiency is the ratio of how much of the energy storage system's potential energy is being stored and supplied as electrical energy, whilst minimizing losses and over cycling. The PV-Battery configuration had a battery utilization efficiency of 74%, with heavy usage of batteries in the absence of PV generation. The PV-Wind-Battery system enhanced the efficiency to 81% due to the reduction of frequency of charging and discharging the battery by wind generation. PV-BB system achieved 85% efficiency by generating supplementary stable electric power with biomass generation. With the combination of several energy sources, the PV-Wind-Biomass-Battery system achieved a battery utilization efficiency of 90%, due to the lower battery stress of storing energy from multiple sources, the lower battery degradation and the longer battery life.

4.3. Discussion of Findings

From the above analysis of the performance, it has been found that the PV-Wind-Biomass-Battery configuration gives the best and sustainable performance among the various combinations of renewable energy systems analyzed. The reasons for this performance are the ability to combine various renewable energy resources with complementary generation characteristics to ensure a stable and continuous power supply under changing environmental conditions. Solar PV panels generate electricity in daylight hours, wind turbines can provide electricity when the wind is blowing and the night time, and biomass can generate dispatchable and controllable electricity, irrespective of the weather. The battery energy storage system also increases operational stability by storing excess energy and providing energy when the generation is insufficient. Such an integrated operation greatly reduces the risk of energy shortages and provides a very reliable electricity supply. Technically, the integrated configuration allows a reliability level higher than 99%, which is very suitable for rural electrification and remote area applications where reliability is a key requirement. This decreases reliance on battery storage alone, lowering the frequency of battery cycling, increasing battery life and optimizing overall system efficiency. In addition, the system has higher flexibility in operation, and can adjust the use of resources and load demand in accordance with different situations. The hybrid setup has a number of significant economic benefits, including fuel efficiency, reduced running and maintenance costs, and the elimination of expensive backup generators that rely on fossil fuels. The capital costs for this system may be more expensive than some simpler system configurations, but the operating cost savings and equipment life can be expected to offset the up-front costs and bring about increased return on investment and economic stability over the life of the project. Ecological advantages are equal. Near zero operational greenhouse gas emissions and significant reduction in fossil fuel consumption are the characteristic of high penetration of renewables. Thus, the system helps to mitigate climate change, enhance the air quality, and minimize environmental degradation. The use of biomass also contributes to sustainable waste management, by providing energy from agricultural residues and organic wastes. The results overall have shown that a diversified renewable energy portfolio significantly enhances the resilience, reliability, economic efficiency, and environmental sustainability of the system. The results underscore the significance of the integrated hybrid renewable energy system as a viable and feasible approach to sustainable rural electrification for sustainable global clean energy transition goals.

5. CONCLUSION

Hybrid Renewable Energy Systems (HRES) are one of the most promising and viable solutions to the continued issues of rural electrification, especially in remote and geographically isolated areas where extension of conventional utility networks is technically challenging and economically unattainable. The findings of this study have shown that a combination of multiple renewable energy sources such as solar photovoltaic (PV) systems, wind turbine generators, biomass power generation systems and battery energy storage systems can greatly enhance the reliability, efficiency and sustainability of the electricity supply chain. Hybrid systems have the ability to integrate various renewable energy sources and their characteristics, mitigating the unpredictability of renewable energy generation and ensuring a more consistent and reliable energy supply throughout the year. The comparative performance assessment carried out in this study has shown that the multi-source hybrid configurations always deliver better performance than the single-source renewable energy systems in all technical, economic and environmental aspects. The PV-Wind-Biomass-Battery configuration was the most favorable one in terms of overall performance, renewable energy fraction, system reliability, energy availability, battery utilization efficiency and reduction of fuel consumption and greenhouse gas emissions. The integration of biomass generation delivers dispatchable renewable power that can be used when the sun isn't shining and wind speeds aren't high enough, and battery storage gives extra flexibility to the system by helping to match energy generation and demand. The integrated configuration provides a reliable power supply with just minimal deficits in energy and without the need for conventional back-up generation. Economically, it can be seen from the results that hybrid renewable energy systems can have higher initial capital costs than the traditional system using diesel energy sources, but through the reduction of fuel costs, lower maintenance needs, less frequent replacement of components and more efficient operation, they still have long-term economic benefits. The lifecycle cost and Levelized Cost of Energy (LCOE) analysis further shows the cost effectiveness of hybrid renewable systems in sustainable rural electrification, thus minimizing the risks of fuel price volatility and uncertainties in

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the fuel supply chain for rural communities. The environmental assessment also emphasizes the significant decrease in carbon dioxide emissions and other pollutants, reflecting the mitigation of climate change, air quality and responsible use of natural resources. In future, ongoing progress in renewable energy technologies, battery storage systems, power electronics and intelligent control systems will further improve the performance and cost of hybrid renewable energy systems. The following studies are recommended for future work: machine-learning-based renewable resource forecasting techniques; artificial-intelligence-based energy management algorithms; smart microgrid architectures; advanced battery degradation models; and real-time optimization frameworks capable of adapting to the dynamic operating conditions. Apart from this, supportive government policies, financial incentives and community participation programs play an important role in realizing a large-scale deployment of hybrid renewable systems. This kind of efforts will be essential in ensuring universal access to sustainable, reliable access to electricity, supporting sustainable rural development, enhancing energy security and making global transition towards clean energy in the next few decades more likely.

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