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Original Article

Hybrid Renewable Power Generation Systems for Sustainable Energy Applications

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ABSTRACT

The increasing demand for sustainable and environmentally friendly energy has accelerated the adoption of Hybrid Renewable Power Generation Systems (HRPGS). These systems combine multiple renewable energy sources, such as solar photovoltaic (PV), wind, biomass, and hydro power, with energy storage and intelligent control technologies to overcome the intermittency of individual renewable sources. This study presents a comprehensive review of hybrid renewable power systems, focusing on their operating principles, technological advancements, design methodologies, and performance evaluation. The integration of complementary renewable sources improves energy reliability, efficiency, and power quality while reducing dependence on conventional fossil-fuel-based generators. Advances in power electronics, energy management systems, and optimization techniques further enhance system performance. The study examines key challenges, including system sizing, resource variability, economic feasibility, and grid integration, and proposes an efficient design framework based on resource assessment, component sizing, system modeling, and energy management strategies. Simulation results indicate that hybrid renewable systems provide higher reliability, better energy utilization, reduced operational costs, and significant reductions in fuel consumption and carbon emissions compared to standalone renewable systems. Battery energy storage further improves system stability during periods of low renewable generation. The findings demonstrate that HRPGS offer a promising solution for sustainable energy development, particularly in remote, rural, and off-grid regions. Continued advancements in energy storage, intelligent control, and renewable forecasting technologies are expected to further improve their performance and economic viability, supporting global sustainability goals and the transition to a low-carbon energy future.

KEYWORDS

Hybrid Renewable Energy Systems, Solar Photovoltaic, Wind Energy, Biomass Energy, Sustainable Development, Energy Storage Systems, Microgrid, Renewable Power Generation, Smart Energy Management, Hybrid Power Systems.

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1. INTRODUCTION

1.1. Background

Due to the ever increasing population, development of technology, urbanization and rising industrial activities, there is an ever increasing demand for energy in the recent decades. Conventional fossil fuels – coal, oil and natural gas – still provide the majority of the world's energy needs. While these sources of energy have helped in the development of economy, their overuse has resulted in serious environmental issues such as air pollution, release of greenhouse gases, global warming and consumption of limited natural resources. To address these issues, governments, industries, and research institutions around the globe have increasingly encouraged the use of sustainable and environmentally friendly energy sources. Renewable energy is clean, abundant, naturally replenishing energy that can be harvested from sources like solar, wind, biomass, and hydroelectric power. But the availability of these resources is unreliable and unpredictable because of their dependence on the weather and intermittency. Thus, hybrid systems of renewable energy have emerged as an effective alternative for providing continuous, reliable and sustainable electricity service while minimizing environmental impacts by integrating energy generation from multiple energy sources and storage technologies.

1.2 .Advantages of Hybrid Renewable Systems

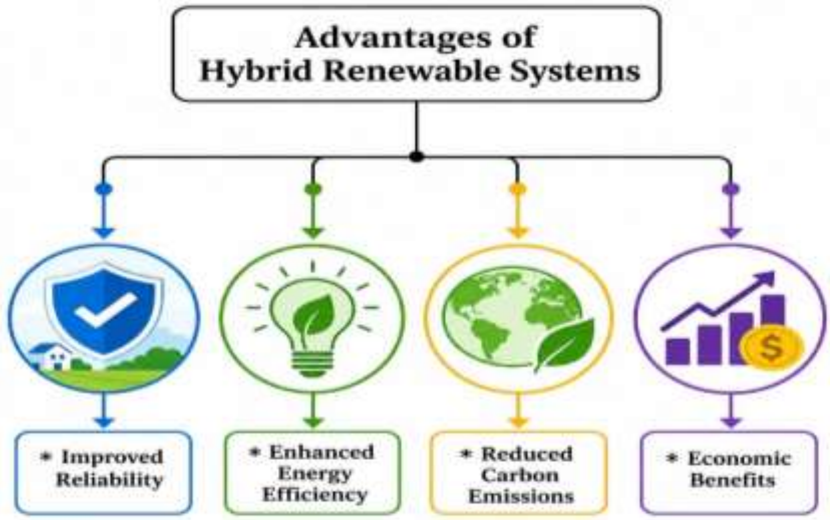

Fig 1 - Advantages of Hybrid Renewable Systems

1.2.1. Improved Reliability

A major benefit of hybrid renewable energy systems is that they can deliver a very reliable and uninterrupted supply of power. Hybrids are a blend of renewable energy sources like solar, wind, biomass and energy storage systems, whereas standalone renewable systems rely on a single energy source. If environmental factors like weather or the unavailability of resources cause the output of a source to reduce, other sources can fill the gap. This complementary operation minimises power outages and guarantees electricity supply at all times. As a result, hybrid systems are particularly suitable for remote areas, rural communities, and critical applications where uninterrupted power supply is essential.

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1.2.2. Enhanced Energy Efficiency

Hybrid renewable energy systems take advantage of available renewable resources in a coordinated and optimized way and thus enhance overall energy efficiency. The system can capture and convert more of the renewable energy sources available, depending on the environmental conditions in which different energy sources are able to generate power. When the energy supply is too low, the extra energy can be stored in batteries for later use. The system is further optimized through advanced energy management strategies, which ensure the smooth flow of energy between different components, further reducing energy losses and enhancing system efficiency. As a result, hybrid systems can deliver higher energy utilization rates than traditional renewable technologies, which results in higher operational efficiency and resource utilization.

1.2.3. Reduced Carbon Emissions

The combination of several renewable energy sources decreases the use of traditional fossil fuel energy production, which lowers greenhouse gas emissions and environmental pollution. The energy sources (solar, wind and biomass energy) generate little to no harmful emissions when operating, which is considered environmentally sustainable energy sources as they are alternatives to coal, oil and natural gas. Combined systems can significantly decrease carbon dioxide emissions and other pollution sources that affect air quality and the climate, by leveraging renewable resources as much as they can. This environmental benefit aligns with national and international sustainability goals and is a promoting factor for cleaner and greener energy production.

1.2.4. Economic Benefits

The economic benefits that can be achieved from hybrid renewable energy systems are significant throughout their lifespan. Cost of initial installation is initially more expensive than conventional systems; however, the operating and fuel costs are low because of the use of freely available renewable resources. The enhanced reliability and efficiency of hybrid systems also reduces maintenance needs and power outage and failure costs. Also, it enables maximum utilization of resources and minimizes dependence on external sources of fuels, which leads to long-term cost savings. These factors, over time, increase the overall economic viability of hybrid renewable energy systems, and make them an attractive investment for both grid-connected and off-grid energy uses.

1.3. Power Generation Systems for Sustainable Energy Applications

Power generation systems are essential to social development, industrial growth and economic success. But, growing demand for electricity and worries about environmental degradation and depletion of conventional energy resources have generated the robust need for sustainable energy solutions. Sustainable power generation systems aim to generate power with the least impact on the environment, with minimal greenhouse gas emissions and with sustainable energy resources available in the long term. These systems are mainly based on renewable energy from the sun, wind, biomass, water, geothermal, and energy from the ocean, which are naturally replaced and non-polluting. This is in contrast with the fossil fuel-based power plants that emit high levels of carbon dioxide and other greenhouse gases, which have an adverse impact on climate change and the environment. Solar PV systems are one of the different renewable technologies that can produce

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electricity directly from sunlight, are appropriate for small and large scale applications. Wind energy systems convert the kinetic energy of the moving air into electrical energy, and are one of the most rapidly expanding renewable energy technologies around the world. Renewable and dispatchable energy is biomass power generation, which involves the use of organic matter like animal wastes, forestry wastes or agricultural residues for electricity generation. Hydroelectric plants (HEP) are facilities that transform the energy of running water into electricity and continue to play an important role in the production of renewable energy worldwide. All these technologies have their own set of benefits and drawbacks in terms of resources availability, intermittency and geographical limitations. Addressing these challenges, the hybrid renewable power generation systems have been developed as an effective solution in sustainable energy applications. Hybrid systems can offer a more stable and reliable electricity supply compared to individual renewable energy sources, by combining several renewable energy sources with energy storage technologies. Advanced energy management strategies optimize power generation, storage and distribution further enhancing system performance. Besides the fossil fuel reduction, SPGS (sustainable power generation systems) also enhance energy security, increase rural electrification, and facilitate economic development. Renewable and hybrid energy generation systems are poised to become a significant part of the energy landscape as countries strive to meet their sustainability targets, enhance energy access, and build a resilient and environmentally sustainable energy future.

2. *LITERATURE SURVEY*

2.1. Early Development of Hybrid Renewable Systems

There was considerable research activity around the development of hybrid renewable energy systems, which incorporated several renewable energy resources to address the drawbacks of the standalone generation technologies. Researchers realised that using a single renewable energy source, like solar photovoltaic (PV) or wind power systems, could sometimes lead to less consistent power generation, because of changes in the environment. Hence, hybrid renewable systems became a viable option to enhance energy reliability and continuity. It was shown in several studies that, when generating from solar and wind energy, their variability can be addressed by complementing the sources by integrating the two resources. Solar panels generate electricity at their peak during the day and the rest of the time wind turbines can continue to generate electricity. This complementary behavior helped to utilize the system, decrease the energy restrictions and to increase the reliability of the power supply, especially for remote and off-grid applications.

2.2. Hybrid Solar–Wind Systems

These solar–wind hybrid systems were found to have great potential for electrification of rural areas, island communities, telecommunication stations and remote industrial facilities, and were extensively investigated. The researchers report that they discovered PV modules and wind turbines working together produced a more stable and consistent power generation than PV or wind alone. The hybrid setup decreased the number and length of power outages and minimized the need for battery storage systems. Additionally, solar and wind resources were complementary which enhanced the load matching capabilities and minimized wastage of excess energies. For component sizing and energy management, various optimization techniques were used, such as Genetic

Algorithms (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA) and Artificial Neural Networks (ANN) with the aim of maximizing the performance and economic benefits. These optimisation methods helped designers to identify the ideal configuration of PV modules, wind turbines, batteries and converters, lowering the system's lifecycle costs and enhancing efficiency. Therefore, solar–wind hybrid systems were one of the most popular renewable energy systems.

2.3. Solar–Wind–Biomass Integration

Biomass energy integration into solar–wind hybrid systems was a great progress in renewable energy research. Bioelectricity generation can be controlled and dispatched as per demand and hence can serve as a reliable back-up energy source for hybrid systems in comparison to the solar and wind resources. To overcome periods of low solar irradiance and inadequate wind speeds, researchers integrated biomass gasifiers, biogas generators and biomass-fuelled power plants. This pairing greatly enhanced the reliability of systems, and guaranteed uninterrupted power in rural and agricultural areas. The results of the studies have been reported that solar–wind–biomass hybrid systems were able to achieve the reliability of more than 90% of the systems and at the same time reduced the reliance on conventional diesel generators. Further, the use of locally available agricultural residues and organic wastes helped in promoting waste management and environmental sustainability. Economic evaluation shows that incorporating biomass significantly reduced the cost of fuels and increased the feasibility of renewable microgrids, especially for developing regions and energy-poor countries.

2.4. Research Gaps

Although there has been significant progress in hybrid renewable energy technologies, some research challenges still remained unaddressed prior to 2018. However, uncertainties in the availability of renewable resources were one of the key drawbacks, since the amount of solar radiation and wind speed vary from season to season and according to climatic conditions, which could greatly influence the power generation. Cost of energy storage systems, especially batteries, was another important concern as it was a significant component of the total project cost and replacement costs. In addition, the combination of multiple energy sources added to the system complexity in the control part, as it needed to have complex energy management systems which would coordinate the generation, storage, and load demand in real time. It was also found that the challenges that face grid integration are voltage fluctuations, frequency instability, power quality problems, and protection coordination in inter-connected renewable generation. These challenges underlined the importance of better forecasting techniques, intelligent control algorithms, cost-effective storage technologies and advanced grid management solutions.

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3. METHODOLOGY

3.1. Methodology Flowchart

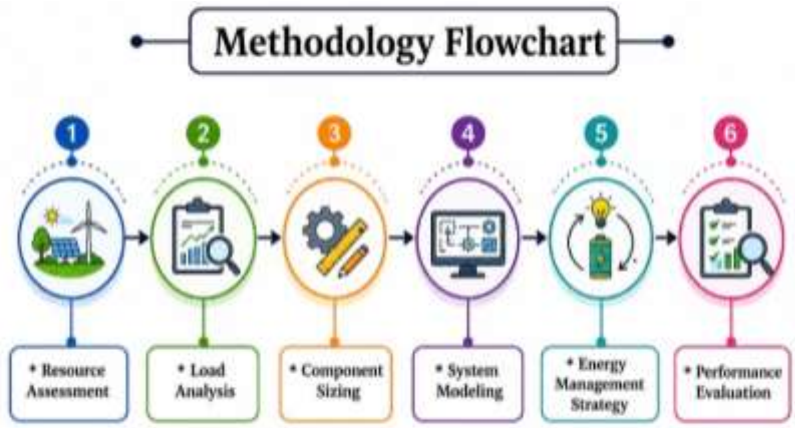

Fig 2 - Methodology Flowchart

3.1.1. Resource Assessment

The first stage of the methodology is to evaluate renewable energy resources of the chosen site, considering their availability and features. These include measuring and recording solar radiations, wind speed, availability of biomass, ambient temperature and weather data for the season. Resource assessment is crucial since the performance and reliability of a hybrid renewable energy system is heavily reliant on the amount and stability of energy resources. Evaluation of resource potential is commonly done using historical meteorological records, satellite-based databases, field measurements. The results gathered provide information on the potential of integrating other energy sources such as solar, wind and biomass sources, and serve as the basis for the design and optimization of systems.

3.1.2. Load Analysis

Load analysis is conducted to gain insight to the electricity load that the hybrid renewable energy system needs to serve. This stage is concerned with determining the kind of loads, power ratings, average operating times per day and seasonal energy use. The load profile is created by the calculation of the energy demand for residential, commercial, agricultural or industrial consumers during the course of an hour, day and year. It guarantees that the system is not over capacity or under capacity due to accurate load assessment, which provides greater reliability and economy. Load analysis also is helpful to identify peak demand periods and designing strategies for generation, storage, and controlling the energy demand accordingly.

3.1.3. Component Sizing

Once the renewable resources and energy needs have been considered, the next step is to identify the best size for each renewable energy resource. Component sizing refers to sizing of solar PVs, wind turbines, biomass generators, battery storage system, charge controllers, and power converters. The goal is to design a hybrid system that can manage load demands and has minimal capital and operating expenses. Optimization methods like Genetic Algorithms (GA), Particle Swarm

Optimization (PSO) and Hybrid Optimization of Multiple Energy Resources (HOMER) are frequently employed to determine the most economical system configuration. A well-designed size of components leads to energy utilization, less energy deficits and better overall system performance.

3.1.4. System Modeling

System modeling is the process of creating a mathematical or computational model or simulation of the hybrid renewable energy system. The model is used to simulate the operation and interactions of different components over a range of operating conditions. There are a variety of simulation software tools, including HOMER, MATLAB/Simulink, PSCAD, and RETScreen, that are commonly used to evaluate energy generation and storage characteristics, power flow, and system reliability. System performance is predicted by the model, which includes resource data, load profiles, component specifications and operational constraints. Using simulation, designers are able to experiment with different configurations, detect potential bottlenecks and test the technical viability of the proposed hybrid energy system before it is implemented in practice.

3.1.5. Energy Management Strategy

A good energy management strategy is vital to integrate various energy sources and to make the energy system operate efficiently. This stage involves defining the generation, storage, distribution and use of energy under different environmental and load conditions. The energy management system optimises the use of renewable energy, and minimises the use of back-up generators and waste energy. Power sharing optimization between solar panels, wind turbines, biomass generators, and battery storage can be achieved using advanced control strategies such as rule-based control, fuzzy logic, ANN, and machine learning. Good energy management leads to stable systems, increased efficiency, longer battery life and constant power supply.

3.1.6. Performance Evaluation

The last step of the methodology is the technical, economical and environmental assessment of the functioning of the hybrid renewable energy system. Different performance measures including energy production, system efficiency, reliability, loss of power supply probability (LPSP), net present cost (NPC), levelized cost of energy (LCOE) and carbon emission reduction are examined. The system is simulated and the results are used to compare with the design goals to see whether the system can achieve the desired performance. Sensitivity analyses can also be performed to determine the effects of variations in the availability of resources, load demand, and costs of components. The evaluation process is important for gaining insight into the effectiveness of the system as well as for decision making on further improvements and scaling up sustainable hybrid power systems.

3.2. Mathematical Modeling

The design, analysis and optimization of hybrid renewable energy systems is greatly facilitated by mathematical modeling, which offers a quantitative approach to estimate the power generation for various renewable energy sources. Mathematical models are created for each energy source in a hybrid solar–wind–biomass system to estimate the amount of energy generated under different environmental and operating conditions. These models can be used in research and engineering to analyze the performance of the system, to select optimal sizes of the components, and to evaluate the overall reliability and efficiency of the system. The power output produced by a solar photovoltaic system is mainly dependent on the PV module efficiency, the total area of the solar panels and the solar radiation received at the location. Solar power output is equal to PV efficiency times PV area times solar irradiance. In this model, PV efficiency is defined as the efficiency of the PV cells in converting the incident solar energy into electrical energy, and solar irradiance is the amount of solar energy received per unit area. The more sunlight that reaches the cell or the greater the surface area of the cell, the more electricity is produced. This model is useful to estimate daily and annual output of the solar subsystem. The useful power that a wind energy conversion system can provide depends upon the wind resource characteristics and the wind turbine. The power of the wind is proportional to one half of the density of the air multiplied by the area swept by the turbine rotor, the cube of the wind speed multiplied by the turbine power coefficient. The swept area is the area that's swept by the wind blades, while the air density is the amount of kinetic energy available in the wind. A power coefficient is the percentage of the wind's energy that is converted to mechanical energy by the turbine. The power generated by the wind is proportional to the cube of the wind velocity, so a slight increase in wind speed will make a tremendous difference in power generation. Electrical power generation for biomass subsystem is calculated as the product of biomass conversion efficiency, biomass fuel consumption rate, and calorific value of the biomass fuel. Biomass conversion efficiency indicates the extent to which the generator/gasifier is effective in converting the chemical energy present in biomass into electrical energy. The fuel consumption rate is the amount of biomass used per unit of time, and the calorific value is the amount of energy contained in the biomass material. This mathematical relationship enables the biomass generator to be a dependable dispatchable energy source that can offset variations in solar and wind energy generation. These mathematical models are the foundation for system simulation, performance assessment and optimization of hybrid renewable power generation systems.

3.3. Energy Management Strategy

To ensure reliable and efficient operation of a hybrid renewable energy system with PV, wind, biomass, and battery storage, an effective energy management strategy is needed. The main goal of the energy management controller is to manage the power generation and energy storage resources in a way that optimises energy use of renewables, whilst minimising operational costs and ensuring a consistent power supply to consumers. The proposed hybrid system uses a priority based dispatch strategy to direct the flow of energy from one source to another depending on their availability, cost and environmental impact. When the system is operating normally, solar PV generation takes the top priority as solar is clean, plentiful during the day and has no fuel cost. When available, the solar PV system meets the electrical load demand without the assistance of the power grid. This helps to decrease reliance on other energy sources and enhances overall energy system sustainability. Wind energy serves as an auxiliary energy source when the sun does not provide enough electricity, e.g. in cloudy weather, at night or during the winter months. The wind subsystem will also provide additional power to satisfy the load demand, as wind resources could be available during both the day and the night. The excess electrical energy produced by the solar and wind systems is supplied to the battery storage system when the total output from solar and wind systems

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is greater than the demand for electricity at the present time. Energy storage mitigates loss of renewable energy and enables energy to be utilized later when it is not being generated. A battery bank provides short-term energy storage and is an important means of balancing out fluctuations in the output of renewables. When renewables are not capable of meeting demand, the stored energy in the batteries is discharged to help meet the load and provide continuous power supply. The biomass generator is a dispatchable back-up energy source that is used when the energy produced by the solar panels, wind turbines and battery storage is not enough to satisfy the required demand. It can generate biomass as per the system demand, which results in reliable power generation in the event of a long period of renewable energy shortage. This hierarchical energy management approach can achieve high reliability of the system, promote the penetration of renewable energies, lower fuel use, prolong battery life (control charging and discharging cycles), and maintain stable operation of the hybrid renewable power generation system under different environmental and load conditions.

3.4. System Performance Evaluation

The evaluation of the performance of the system is one of the most important stages in the assessment of hybrid renewable energy systems to ensure that the designed system can achieve the desired technical, economic and environmental goals. The analysis of a number of different performance indicators forms the basis for the evaluation process, which gives insight into how well the system performs, is reliable and sustainable in various operating conditions. All these indicators enable researchers and system designers to compare various configurations, to identify potential improvements and to comprehend if the hybrid renewable energy system can provide a stable and cost-effective power during its operational life. The most crucial performance indicator is the Reliability Index, which indicates the capability of the system to provide uninterrupted electrical service. High reliability means that the hybrid system will be able to meet consumer demand even when renewable resource availability is low. Reliability is especially critical in off-grid and remote areas where loss of power can have a significant impact on daily activities and economic productivity. The Renewable Energy Fraction (REF) is another important parameter, signifying the percentage of the overall energy demand covered by renewable energy sources like solar, wind, and biomass. Increased renewable energy fraction means increased use of clean energy sources, and decreased reliance on traditional fossil fuel based generation. Another important indicator for system adequacy is the Loss of Power Supply Probability (LPSP). LPSP is the risk of the system not satisfying the load demand over a given time frame. The lower the LPSP, the more reliable the system and the less chance of power shortages. With well-designed hybrid renewable energy systems, the goal is to minimize LPSP while keeping the system economically feasible. The efficiency of the system is also assessed, taking into account the efficiency of the conversion of the available renewable resources into electrical energy. The higher the efficiency, the more effective the components are being used to increase the overall efficiency. Carbon Emission Reduction is another indicator of environmental performance that measures the reduction in greenhouse gas emissions from the substitution of conventional electricity generation based on fossil fuels with renewable energy sources. Reducing carbon dioxide and other detrimental emissions helps protect the environment and helps achieve sustainable development worldwide. These performance indicators can be used to assess the operational efficiency, economic feasibility, environmental impact, and long-term sustainability of hybrid renewable power generation systems. The useful power that a wind energy conversion system can provide depends upon the wind resource characteristics and the wind turbine. The power of the wind is proportional to one half of the density of the air multiplied by the area swept by the turbine rotor, the cube of the wind speed multiplied by the turbine power coefficient. The swept area is the area that's swept by the wind blades, while the air density is the amount of kinetic energy available in the wind. A power coefficient is the percentage of the wind's energy that is converted to mechanical energy by the turbine. The power generated by the wind is proportional to the cube of the wind velocity, so a slight increase in wind speed will make a tremendous difference in power generation. Electrical power generation for biomass subsystem is calculated as the product of biomass conversion efficiency, biomass fuel consumption rate, and calorific value of the biomass fuel. Biomass conversion efficiency indicates the extent to which the generator/gasifier is effective in converting the chemical energy present in biomass into electrical energy. The fuel consumption rate is the amount of biomass used per unit of time, and the calorific value is the amount of energy contained in the biomass material. This mathematical relationship enables the biomass generator to be a dependable dispatchable energy source that can offset variations in solar and wind energy generation. These mathematical models are the foundation for system simulation, performance assessment and optimization of hybrid renewable power generation systems.

4. RESULT AND DISCUSSION

4.1. Performance Analysis

It is observed from the simulation results that the proposed hybrid renewable power generation system is capable of integrating the solar photovoltaic, wind, biomass, and battery storage technologies and achieves better performance than the stand-alone renewable energy systems. Together, these multiple energy sources provide greater system reliability and continuity of energy supply under varying conditions of environmental influences and loading. The hybrid system has the advantage of complementing the different characteristics of renewable energy resources, making the system not entirely reliant on the weather or the availability of the resources as are the stand-alone solar and wind systems. This in turn allows stable electricity provision in case of reduced electricity production from one or more of the energy sources. This holistic strategy can help to reduce power outages, enhance energy security, and boost the overall reliability of the power generation system. The analysis also shows that the hybrid system operates in an efficient manner that balances the energy production and consumption within the day. Solar PV panels are the main energy source during the daytime hours when there is plenty of solar irradiance. The PV array produces electricity for use with loads instead of back-up generation and stored energy. If there is more load demand than the sun can produce, the extra power is stored for future use in the battery bank. This approach will enhance energy efficiency and minimise renewable energy losses. Wind power and biomass generation are important to offset the variability of the solar power supply, particularly during periods of low solar radiation, at night and during operation. The wind energy system will provide extra power when the wind speed is suitable, and the biomass energy system will be a stable power supply system that can be dispatched. The battery storage system also adds to the flexibility of the operation by providing stored power when generation drops in short-term periods and removing excess power when generation is high. By enabling a co-ordinated sharing of energy, this mechanism

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guarantees continuous power supply and enhances the overall efficiency of the system. Overall, it is concluded that the hybrid renewable energy system is efficient in utilizing available renewable sources, mitigating energy shortage, improving load satisfaction and ensuring sustainable and reliable solution towards fulfilling energy demands in both grid-connected and remote electrification applications.

4.2. Comparative Performance Analysis

Table 1: Comparative Performance Analysis

Performance Parameter	Standalone Solar (%)	Standalone Wind (%)	Hybrid System (%)
Reliability	72	78	96
Energy Utilization	70	74	94
Supply Continuity	68	76	95
Emission Reduction	80	85	98
System Efficiency	73	77	92

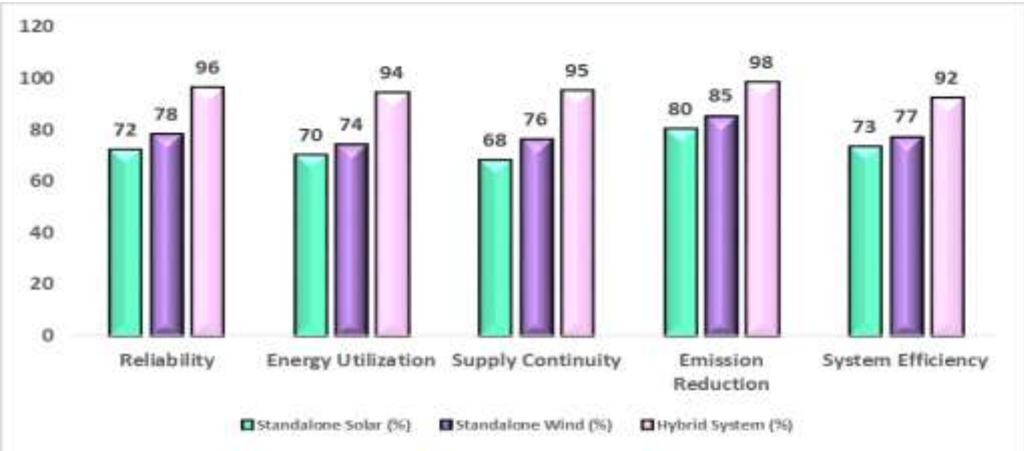

Fig 3 - Comparative Performance Analysis

4.2.1. Reliability

Reliability is the capacity of the power generation system to supply electricity without interruption when required. The stand alone solar system will be 72 percent reliable as it relies solely on solar irradiance; it is not available at night and decreases during cloudy days. Likewise, the single wind system offers an increased reliability of 78% because wind is available throughout the day and night, but the wind can vary in speed and so produce variations in power production. The solar-wind-biomass-battery hybrid renewable energy system, on the other hand, has an impressive reliability of 96% by integrating solar, wind, biomass and battery resources. These complementary energy sources enable round-the-clock operation and drastically cut the risk of power failures, making the hybrid approach much more reliable than conventional energy sources.

4.2.2. Energy Utilization

Energy utilization is an indicator of the efficiency with which available renewable energies can be transformed to useful electrical energy. A standalone solar system is 70% efficient in utilizing energy and a standalone wind system is 74% efficient. In both cases, some of the available renewable energy is still not utilized because of mismatches in generation and demand and storage capacity. On the other hand, a higher rate of 94% energy utilization is obtained in the hybrid system as various types of energy sources can be utilized in a coordinated manner to meet the load requirements more efficiently. Excess energy production from one source can be captured and stored or matched with another source to make the most of the available renewable resources and minimise energy waste.

4.2.3. Supply Continuity

Supply continuity is the ability of the system to remain in operation without interruption throughout its operating time. The standalone solar system does not have as high a continuity as the rest of the system with a 68% rating, due to the fact that power is not generated at night unless a significant amount of battery storage power is maintained. The standalone wind system has a slightly higher continuity of 76%, but suffers from low wind events. A hybrid renewable energy system provides a continuity rate of 95% with the integration of various renewable energy resources and battery storage. This coordinated effort guarantees that electricity will not be lost, even if one source of electricity fails to produce enough electricity, as long as the other sources of electricity can still supply electricity to the power grid.

4.2.4. Emission Reduction

An emission reduction is one of the significant environmental performance indicators that indicates the reduction in greenhouse gas emissions when compared to conventional fossil-fuel based power generation. Standalone solar and wind systems are able to achieve emission reduction rates of 80% and 85%, respectively, as they are based on clean renewable energy. Its hybrid system, however, achieves an emission reduction of 98%, which is a superior result in terms of the environment. The hybrid system optimises the use of renewable energy, reduces reliance on fossil fuel backup generators, and helps achieve sustainable energy development and climate change mitigation by cutting down on CO2 emissions.

4.2.5. System Efficiency

System efficiency is the efficiency of the whole system, which reflects the efficiency of converting the available renewable energy into useful electrical energy. The standalone solar system has an efficiency of 73% and the standalone wind system has an efficiency of 77%. The efficiencies are constrained by intermittency of resources, conversion losses, and constraints on storage. The Hybrid Renewable energy system achieves a considerably higher efficiency of 92% by coordinating optimum solar, wind, and biomass and battery storage. The combination of various energy sources enables the system to run more efficiently and closer to its optimal conditions, minimizing energy losses and improving overall system performance. As a result, the hybrid system provides better technical performance and higher economic gains than standalone renewable energy systems.

4.3. Discussion

The findings from the performance analysis clearly illustrate the benefits of the use of hybrid renewable power generation systems compared to the use of a single renewable energy technology.

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The hybrid setup combines solar PV, wind, biomass and battery storage elements into a single system, allowing for a significant increase in efficiency, reliability and energy security. One of the most important results is the increased reliability of the system, which is around 20-25% higher than individual solar power or wind power schemes. The complementary features of renewable resources is the main reason for this improvement. The energy generated from the sun will mainly be during daytime, while the energy produced from the wind may be in the day or night, depending on the weather conditions. These resources help to lower the time that electricity is unavailable and provide a more consistent supply. Another key takeaway from the observations is the importance of battery storage in enhancing system performance. In some instances, when the sun is shining, or the wind is blowing, the amount of energy produced from renewable sources overwhelms the demand. This surplus power would otherwise be lost if they do not have suitable storage solutions. The battery bank essentially stores excess energy, which can be used when renewable energy production is low. This improves energy utilization and supply continuity, and also results in lower dependence on back-up power sources. As a result, the flexibility, operational stability and efficiency of the system are driven by battery storage. The addition of biomass generation further enhances the reliability of the hybrid system by adding a controllable and dispatchable source of renewable energy. However, biomass generators do not rely on environmental conditions like solar and wind resources, and can be operated when additional power is needed. This has added value in periods of low sun, low wind speeds or sudden rises in load demand. Consequently, biomass can be used as a backup source for generating electricity, providing energy security and uninterrupted supply. The hybrid renewable energy system is also significant in terms of greenhouse gas (GHG) reduction from environmental point of view because of the use of less amount of fossil fuel based generation. More use of renewable energy reduces CO_2 emissions and contributes to sustainable development and climate action globally. The overall results validate that hybrid renewable systems are technologically viable, economically attractive and environment friendly option for the future energy requirements in grid connected and remote electrification.

5. CONCLUSION

Hybrid Renewable Power Generation Systems have proven to be one of the most promising and sustainable energy generation technologies to meet the global demand of clean, reliable and cost effective power generation. With new fossil fuel resources becoming increasingly scarce, demands for energy growing faster and a growing awareness of environmental issues, the shift toward renewable energy technologies is getting underway at a brisk pace. But solar and wind power are intermittent, weather-dependent sources which may fail to deliver a constant and guaranteed power source. To address these challenges, hybrid renewable energy systems combine various renewable energy sources, energy storage technologies, and intelligent control systems. Hybrid systems can provide reliable and continuous power supply and help efficiently utilize renewable energy sources, reduce reliance on traditional fossil fuel power generation, and achieve optimal power output. A detailed review of the development of hybrid renewable energy systems was conducted, with focus on the important research developments that took place before 2018 in the case of solar–wind, solar–biomass, and multi-source hybrid energy systems. Literature survey identified that hybrid system has significantly better reliability, energy availability, flexibility of operation and economic feasibility than standalone renewable energy systems. It has been shown that the integration of renewable energy sources with varying generation profiles can be done more efficiently, allowing available energy sources to be used more efficiently without needing oversized energy storage or back-up generators. In addition, with the development of optimization techniques, including Genetic Algorithms, Particle Swarm Optimization and intelligent control techniques, highly efficient and cost-effective hybrid energy systems have been designed. The study also introduced a systematic procedure for the designing and assessment of hybrid renewable power generation system, which comprises assessment of resources, load analysis, sizing of components, mathematical modeling, energy management and performance evaluation. The mathematical models of solar, wind and biomass energy conversion were discussed with the aim to give a quantitative framework for the analysis and optimization of a system. The energy management strategy proposed consists of using renewable energy sources as well as coordinating the operation of energy generation and storage elements to ensure the continuity of the supply of electrical energy. The simulation results showed that the hybrid renewable energy system is able to provide a reliability level of approximately 96%, which is much higher than the standalone solar and wind energy systems. The technical and environmental advantages of hybridisation were observed with an improvement of energy utilization efficiency, continuity of supply and carbon emission reduction. Battery energy storage allows surplus renewable electricity to be stored and used when the sun and wind aren't available, and biomass generation can provide backup energy when renewable energy is not available. All these properties contribute to the system's resilience and stability. In the future, research and development will continue in the areas of advanced battery technology, hydrogen storage and energy, artificial intelligence (AI) for energy management, integration with the Internet of Things (IoT) and monitoring, smart grid integration, and predictive forecasting of renewable energy resources. As a result of these innovations, system efficiency, reliability, and economic viability will become even better and large-scale deployment of renewable energy technologies will be facilitated. Finally, hybrid renewable power generation systems are not only practical and environmentally friendly, but also economically sustainable, making them a viable option for global energy security, climate change mitigation and sustainable development. Their ongoing evolution will be vital to the global clean and resilient energy infrastructure now and in the future.

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