Remittances Review
January 2024,
Volume:10 , No:1 ,pp.195-209
ISSN: 2059-6588(Print)| ISSN: 2059-6596(Online)

Received: 12 April 2024, Accepted: 26 December 2024
DOI: https://doi.org/10.47059/rr.vx9i2.10

HYBRID ENERGY SYSTEMS FOR SUSTAINABLE POWER MANAGEMENT: A SIMULATIVE ANALYSIS

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Abstract --- Hybrid energy systems have emerged as a promising solution for sustainable power management by integrating multiple renewable and non-renewable energy sources to optimize energy generation, reduce costs, and minimize environmental impact. This study conducts simulative analysis to evaluate and determine which combination of solar power, wind turbines, battery storage ancillary to biomass and the comprehensive system performs best. A complete evaluation of both scheduling methods and financial implications and environmental impact determines the most efficient energy management solution. The researchers utilized MATLAB/Simulink dynamic modeling framework to conduct performance assessments of each system case. Hybrid configurations between multiple systems show better reliability and more affordable operation and cause lower CO_2 emissions when compared to single standalone setups. A combined system offered the most perfect combined performance by maximizing renewable energy usage together with affordability and sustainability benefits. System performance analysis via sensitivity testing demonstrated how changing renewable energy levels affects the operating results. The research demonstrates the potential sustainability of hybrid energy systems but additional optimization strategies remain necessary for practical application success.

Keywords --- Hybrid Energy Systems, Renewable Energy, Biomass Energy, Power Management, Simulative Analysis, Sustainability

I. INTRODUCTION

A. Background

With the global move toward sustainable energy solutions, Hybrid Energy Systems (HES) that interface numerous renewable energy sources for stable and effective energy generation have adopted at increasing rate [1]. The need for cost effective solutions available at the right price with perfect balance to energy security, cost effectiveness, and environmental impact is identified by the rising global electricity demand and climate change concerns. Both standalone renewable sources such as solar and wind energy have huge potential, but please, caveat emptor, they are intermittent, and the continuous power supply requires their hybrid integration [2].

Solar and wind power are both abundant but limited to daytime and unpredictable wind patterns, respectively, causing energy generation from these sources to be fluctuating. However, high initial costs and capacity limitations of battery storage systems help mitigate these fluctuations [3]. On the other hand, biomass energy converts organic materials to produce a stable electrical energy output which complement other intermittent sources [4]. However, biomass systems are not viable unless there is sustainable supply of the biomass and efficient energy conversion devices.

Some of the renewable sources are integrated in order to act as Hybrid microgrids which would make them also receive a steady power supply resulting in their reducing a dependence on fossil fuels and also enhancement of their energy resilience. By evaluating numerous hybrid energy configurations based on MATLAB/Simulink's simulation, this study aims to establish the most suitable system for the sustainable power management.

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B. Problem Statement

While environmentally beneficial, renewable energy sources have many difficulties in terms of energy reliability and integration into existing power systems. Solar and wind power are subject to unpredictable fluctuations, and a stable supply of power requires a storage system or additional power source [2]. However, the battery storage solutions are effective but with high cost and degradation issues which are not very feasible for long term applications without optimization techniques [3]. The energy generated by biomass is continuous, however, it has to go through sustainable fuel management and conversion efficiency constraints [4].

The majority of these studies have studied standalone renewable sources or a two-source hybrid system which leads to a research question: What are the comparative advantages and disadvantages to an active multi source hybrid microgrid? The objective of this research is to bridge that gap through the assessment of the technical and economic viability of both solar, wind, battery and biomass energy at an individual basis, and in a fully integrated hybrid system. This study is not based on an optimization technique approach, but mainly on real world performance assessment via simulations.

C. Aim

Simulative analysis has been performed in this research to evaluate the performance, cost effectiveness and environmental impact of several hybrid energy configurations for evaluation purposes. The study examines the following cases:

- Case 1: Solar-Grid System – A photovoltaic (PV) system connected to the grid, which provides renewable energy integration while maintaining grid support during low solar availability.
- Case 2: Solar-Battery System – A standalone system where battery storage balances energy availability and compensates for solar intermittency.
- Case 3: Solar-Electrolyzer-Battery System – Excess solar energy is converted into hydrogen via an electrolyzer for energy storage, allowing better utilization of renewable power.
- Case 4: Biomass Model – A biomass-based power system designed to generate continuous energy output, mitigating fluctuations in other renewable sources.
- Combined System: Hybrid Integration – A fully integrated system combining solar, wind, battery, and biomass energy to maximize reliability, reduce emissions, and lower costs.

The research evaluates energy efficiency together with environmental impact and economic viability through simulations of individual cases and the entire integrated system. The study results will determine which power configuration works best for sustainable systems.

D. Significance

Energy sustainability together with cost efficiency and environmental preservation depends on hybrid energy systems. The combination of different energy sources known as hybrids operates with improved dependability and higher resource accessibility in addition to better capability to handle volatile energy consumption needs [1]. Power generation resulting from solar, wind, biomass and battery storage integration operates uninterrupted which minimizes reliance on traditional fossil fuel-based power grids and reduces carbon emissions in the environment [2].

The study creates important practical value that benefits energy policymakers together with researchers and industries associated with this field. The analysis evaluates different renewable energy combinations to determine the optimal system types that match different energy requirements. Research outcomes enable the development of cost-efficient microgrid systems that maintain high resilience in power operations especially in areas where electrical grid connectivity remains unstable. The evaluation of biomass standalone energy source stands crucial because it delivers power security through waste recovery systems [3].

The research promotes hybrid energy system knowledge through an examination of different renewable power solutions while demonstrating their positive and negative aspects. The performance analysis through MATLAB/Simulink-based simulations produces precise results which businesses can implement during their energy planning operations and infrastructure projects. The research delivers useable recommendations about scalable sustainable hybrid energy solutions through its comparative approach instead of optimization techniques [5].

II. LITERATURE REVIEW

This section performs an extensive review of hybrid energy system research that includes detailed investigations into technical aspects along with economic evaluations and sustainability assessments. The research presents an understanding of hybrid system modeling frameworks and optimization at first then explores urban and rural applications together with innovative management approaches and advanced implementation of green hydrogen and smart controllers. The combined findings from previous research demonstrate both field progress and open areas which the current research addresses according to critical examination.

A. Modeling and Optimization Frameworks

1) An Overview on Optimal Modeling of Hybrid Renewable Energy Systems for Enhancing Energy Management Strategies (2024)

The research by Petrović et al. (2024) utilizes software platforms HOMER for conducting simulations and conducting optimization procedures and sensitivity-based assessments of renewable and fossil fuel integration. Scenario modeling dynamics enable better power reliability and reduced operating costs according to their findings while demonstrating economic benefits of using cost-optimized approaches. Petrović et al. (2024) dedicate their study to sophisticated optimization methodology while potentially concealing easier operational practices when operating without advanced control systems. The present research adopts a simulation-based evaluation method without complex scheduling algorithms despite its different focus from Petrović et al. (2024). [6]

2) A Comprehensive Review of the Design and Operations of a Sustainable Hybrid Power System (2023)

The authors Onaolapo et al. (2023) investigated hybrid power system capabilities to reduce carbon emissions in European and African electricity networks. The review presents comprehensive instructions about strategic planning alongside resource identification strategies and best practices when integrating numerous renewable energy technologies. The article presents extensive information about policymaking together with resource synergies yet)data aggregation does not enable side-by-side comparison of single or multi-source renewable power setups operated under standard conditions. This research solves the unmet requirement for direct evaluation by performing standardized simulation analysis of solar and wind alongside battery storage and biomass power generation units. [9]

3) Optimal Energy Management Strategies for Hybrid Power Systems Considering Pt Degradation (2024)

The research by Sheng et al. (2024) investigates PEM fuel cell platinum degradation through a one-dimensional degradation modeling approach to sustain long catalyst life and decrease fuel expenses. The procedures used by this study form the basis for fuel-cell technology but apply minimally to standard power systems that rely on solar panels wind turbines batteries and biomass generators. The authors present detailed component modeling to study complex hybrid systems but their work does not include standard microgrid practice. The valuable platinum-focused research from this study does not address simpler hybrid generation systems which typically lack their specialized technological components. Such systems would benefit better from comparing different options. [11]

4) Optimization of Integrated Hybrid Systems Using Model Predictive Controller (2023)

The authors Birunda Mary et al. (2023) implemented predictive control procedures that reduce forecast errors in solar-wind hybrid systems. The mathematical system from Birunda Mary et al. (2023) results in lower discrepancies in power output predictions but requires dependable computer systems while ignoring biomass and battery storage capabilities. The findings become less applicable for multi-resource microgrids because the study only examines solar and wind power resources as its single research focus. In contrast to this research model we have adopted a sweeping evaluation technique to analyze fundamental operations for solar wind battery and biomass systems separately and collectively in one framework. [10]

B. Intelligent Control and Management

1) Sustainable Hybrid Energy System Based on Green Hydrogen with Efficient Management Using AI and IoT (2023)

Afia and team (2023) created a system that combines solar power with batteries and green hydrogen storage under AI and IoT management to achieve real-time monitoring and adaptive power flow control. Their method reaches optimal operational effectiveness since it regulates generation and consumption in real-time. The technical complexity of this solution depends on extensive technological capabilities coupled with reliable communication networks hence becoming unsuitable for deployment in remote and poorly developed regions. The current research analyzes main renewable resources through direct simulation outputs while avoiding complex AI-based controllers. [8]

2) A Coordinated Optimal Operation of a Grid-Connected Wind-Solar Microgrid Incorporating Hybrid Energy Storage Management Systems (2023)

Abdelghany et al. (2023) applied model predictive control in microgrids which consist of wind power along with solar panels combined with hybrid energy storage mechanisms. Coordinated dispatch according to their findings enables substantial savings while providing enhanced stability performance. The specific scheduling methods presented in this paper alongside its omission of biomass integration reduces its potential use across different real-world applications. The research provides room for the current investigation because it fails to examine basic operational principles or biomass stabilizing properties or to maintain simplicity in its computational approach. [19]

3) Modelling and Simulation for Energy Management of a Hybrid Microgrid with Droop Controller (2023)

Energy balancing in a battery-solar-wind microgrid is handled through droop control according to Saadaoui et al. (2023). The

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research adopts droop control because it responds well to distributed generation systems yet concentrates exclusively on load distribution dynamics rather than general expense and environmental effect measurements. The analysis does not include biomass as a possible energy source which overlooks steady power generation potential. The study aims to fill the gap regarding direct comparison between multiple energy sources through its research approach. [20]

C. Techno-Economic Evaluations

1) Investigating the Sustainability of Urban Energy Generation with Techno-Economic Analysis from Hybrid Energy Systems (2023)

The study by Tewary (2023) demonstrates how urban photovoltaic arrays linked to diesel generators decrease dependence on the grid as well as reduce emissions in built-up areas. The economic feasibility of PV-diesel synergy is demonstrated in the study yet it fails to deeply investigate renewable energy combinations without diesel. Because the system lacks biomass and wind power it focuses on urban energy systems which remain dependent on fossil fuels for backup. The current research advances previous work by integrating modeling of diverse resource combinations that include wind turbines along with battery storage and biomass attributes. [7]

2) Performance Analysis of a Hybrid Renewable-Energy System for Green Buildings to Improve Efficiency and Reduce GHG Emissions with Multiple Scenarios (2023)

The HOMER modeling tool enables Al-Rawashdeh et al. (2023) to prove that solar and wind combination systems decrease greenhouse gas emissions in green buildings. The multiple scenario methodology supports environmental planning with buildings but does not address permanent resources such as biomass nor provide insight into total microgrid requirements. The article successfully demonstrates dual renewable synergy yet fails to provide the detailed research necessary for single-source baseline investigations or battery plus biomass integration because such integration becomes essential for stable energy delivery in uncontrolled areas. [12]

3) A Study on Modeling and Simulation of Hybrid Solar-Wind System under Variable Load Condition (2024)

The paper by Mondal (2024) demonstrates solar and wind and diesel generators working in unison with fluctuating electrical demands. The power system delivers better reliability than using individual solar and wind sources yet it needs diesel backup generators during generation gaps. This paper omits an analysis of biomass as a stable renewable backup option to replace the environmentally and economically unfavorable use of diesel despite its introduction. The present work includes biomass within a combined system to provide an environmentally friendly solution for managing system load variations. [15]

4) A Hybrid System Combining Photovoltaic, Wind Turbine, Diesel Generator, and Battery Storage Technologies (2024)

Bhoi (2024) presents a hybrid system composed of multiple components to decrease prices which purposefully targets rural locations. The study shares a common limitation with diesel-based integrated research since the continuous use of fossil fuels hampers potential carbon reduction benefits. A failure to incorporate biomass indicates the researchers have not addressed how sustainable organic feedstock power generation promotes diesel fuel elimination. The simulation approach presented here addresses biomass potentials in conjunction with solar and wind power systems which Bhoi (2024) neglected in his work. [16]

D. Resource Integration Strategies

1) Independent Hybrid Energy Systems Using Reliable Renewable Energy Sources for Providing Sustainable Power and CO2 Emission Reduction (2023)

Mohamedyaseen et al. (2023) recommend resource mapping for identifying suitable renewable energy pairs in India because solar-wind combinations backed by batteries effectively decrease carbon emissions. The authors acknowledge biomass as a powerful baseline generator but their personalized analysis does not show individual performances of assets nor provide standardized modeling methods to evaluate them as a whole. The current research introduces an uniform simulation framework which allows evaluation of individual resources along with multiple resource systems. [14]

2) A Coordinated Optimal Operation of a Grid-Connected Wind-Solar Microgrid Incorporating Hybrid Energy Storage Management Systems (2023)

The authors Abdelghany et al. (2023) demonstrate detailed coordination techniques between wind power and solar energy aided by state-of-the-art storage capabilities. Although it provides more reliable service the design approach features a restricted operational scope through its complex implementation without biomass integration. The current study adds biomass resources to its analysis to prove that stable generation can reduce the dependency on complex control systems and substantial storage capacity. [19]

3) Energy Management of Photovoltaic-Battery System Connected with the Grid (2022)

A photovoltaic battery system connected to the grid enhances both power supply reliability as well as prevents brief power fluctuations according to Hamed et al. (2022). Battery storage improves power system reliability according to the authors but they did not explore how adding stable resources like biomass could reduce battery deployment expenses or extend battery lifetime. The current research tests both biomass-only operation alongside combined operations to evaluate if biomass systems can reduce battery infrastructure needs. [17]

4) Hybrid Renewable Power Generation and Modeling (PV and Wind) (2023)

Alwakeel et al. (2023) create wind-solar synergy models that employ advanced control algorithms to improve both performance efficiency and harmonic distortion reduction. Specialized controllers yield powerful 97.5% efficiency results for this solution however these controllers operate differently from standard comparison frameworks which optimize single and multiple energy sources. The study approach neglects how additional biomass and battery storage could strengthen the microgrid's stability at a time when this aspect remains a priority for the combined scenario analysis. [18]

E. Research Gap

Different studies throughout academia demonstrate how hybrid power systems decrease atmospheric carbon emissions while enhancing power grid stability rates. The evaluation methods in numerous studies include complex optimization, specialized controllers and local resource limitations that minimize the understanding of how each resource operates alone or combined in basic applications. Most studies in this field analyze no more than three sources alongside diesel backup power generation systems while overlooking biomass as a complete renewable solution baseline. Studies that discuss biomass do not usually analyze stand-alone solar, wind, battery and biomass systems in detail before combining them into one microgrid. This study addresses this gap by conducting simple simulations which explore four individual systems including solar-grid, solar-battery, solar-electrolyzer-battery and standalone biomass before moving onto the combined system of solar, wind, battery and biomass without advanced scheduling mechanisms. The research investigates how simultaneous renewable energy integration produces natural efficiencies and associated economic as well as environmental benefits that enhance system stability and financial return potential.

III. METHODOLOGY

The paper presents a simulation-based method for analyzing technical aspects along with economic and environmental results of renewable energy systems in microgrid operations. The research analyzes five power generation systems that include (i) Case 1 Solar-Grid system, (ii) Case 2 Solar-Battery system, (iii) Case 3 Solar-Electrolyzer-Battery system, (iv) Case 4 stand-alone Biomass system and (v) Case 5 Combined Hybrid System consisting of solar, wind, biomass with battery storage and grid interconnection technology. A high-level simulation environment operates within the framework that implements models and control logic through outputs which generate on an hourly basis during a 24-hour timeframe.

A. Research Approach and Simulation Environment

The study examines renewable energy system configuration operational baselines through a simulation approach under actual load and resource scenarios. The simulation infrastructure enables detailed system representation through which officials execute time-based simulations to generate output statistics including power generation levels and energy storage variability and operational expenditure with carbon dioxide release. The evaluation method examines individual configuration performance although it does not employ complex optimization procedures. Throughout the simulation period of 24 hours which progresses in one-hour increments the model finds equilibrium between precise modeling and computational throughput.

B. Case Study Descriptions

The research investigates five separate system configurations that fully demonstrate renewable energy integration methods.

1) Case 1: Solar-Grid System

A photovoltaic array powered by solar irradiance information produces electricity in the Solar-Grid system. The system transforms sunlight exposure into electrical output by means of a conversion efficiency value that measures its performance. The system connects to the grid-operated power system to obtain extra power when its generated energy falls short of necessary load requirements. This setup allows performance evaluation of solar energy as a main renewable power source while measuring dependency on the power grid and operational expenses and greenhouse gas emissions.

2) Case 2: Solar-Battery System

The Solar-Battery system connects stored energy units to photovoltaic solar power generation arrays. This system design enables storage of additional solar energy when irradiance levels are high which then becomes available to support the load during low solar output conditions. The model includes an evaluation of battery operation through SoC measurement alongside efficiency analysis and capability restrictions. The analysis determines how battery storage affects grid independence and operational expenses and deals with solar power intermittency.

3) Case 3: Solar-Electrolyzer-Battery System

This configuration develops the Solar-Battery system through the addition of an electrolyzer unit. A surplus of solar-produced electrical energy can be transformed by the electrolyzer into hydrogen which functions as stored energy. The stored hydrogen produces electrical power that lowers community dependence on the electricity grid. The electrolyzer achieves a conversion efficiency level of 65–70%. The model monitors how power travels through the PV array as well as the electrolyzer system and the battery storage before it reaches the reconversion process therefore allowing better assessment of hydrogen's role as an additional energy storage method.

4) Case 4: Biomass System

Continuous electrical power generation through the Biomass system uses either organic waste or agricultural residues as its primary feedstock. A provided biomass feed rate at the ton per hour measurement gets transformed to mass flow rate in kilograms per hour before the calculation of the available energy multiplies the mass rate by the biomass's defined lower heating value of 15 MJ/kg. The conversion to electrical power at the rate of kW proceeds from energy measurements (in MJ/h) through the factor of 0.27778 kW per MJ/h and an efficiency value (28%) of biomass conversion. The model determines fuel usage alongside CO_2 emissions at 0.10 kg CO_2/kWh and operating expenses from current market rates during its calculations. The case serves as a tool for predicting how biomass operates as a dependable renewable resource when combined with intermittent energy sources.

5) Combined Hybrid System

A single microgrid controller links solar power plus wind generation along with biomass energy systems with battery storage components. The design incorporates solar and wind intermittency by teaming it with biomass stability and battery storage adaptability. The dispatch strategy begins by utilizing renewable power to satisfy the load requirements while sending excess power to battery storage which remains incomplete supply gets fulfilled from the grid. At the conclusion the model produces comprehensive evaluations which encompass energy efficiency alongside operational expenses and environmental influences of the whole system.

C. System Models and Component Descriptions

This section describes each important simulation model used in the analysis.

1) Solar PV Model

The solar PV model transforms solar irradiance measurements of W/m² into electrical power outputs of kW through an efficiency-based conversion method. The model includes temperature-based effects and wiring and shading losses for optimizing realistic performance evaluations. The model generates power availability information for each hour that goes to Solar-Grid and Solar-Battery operation.

2) Wind Energy Model

The wind model measures power output through wind speed data when wind energy forms part of the system configuration. Power output from electrical turbines depends on the turbine performance curves that show how wind speed affects electrical generation. The simulation requires three key turbine parameters namely cut-in speed and rated speed and cut-out speed for precise wind condition modeling.

3) Battery Storage Model

The battery storage model monitors the continuous changes in battery state-of-charge (SoC) from moment to moment. The system contains mathematical expressions which measure charging and discharging effectiveness and monitors battery operations inside secure operating boundaries. The battery model plays an essential role in determining the power stabilizing capabilities of renewable electricity generation when applied to Solar-Electrolyzer-Battery systems and Solar-Battery setups and to the Combined Hybrid System.

4) Biomass Energy Model

Through the biomass energy model the electrical output derives from converting biomass feedstock into energy. The first step of the process involves converting measurements of biomass feed rate expressed in tons per hour into mass flows measured in kilograms per hour. The calculation determines available energy as a product between mass flow and biomass LHV (15 MJ/kg rate). The computed MJ/h energy quantity undergoes conversion using a 0.27778 kW per MJ/h factor and experiences subsequent reduction through the 28% biomass conversion efficiency. As part of its operation the model generates calculations for biomass energy CO_2 emissions and the associated operational expenses.

5) Electrolyzer Model

An electrolyzer (Case 3) operational with solar power systems allows the electrolyzer model to transform surplus solar power into hydrogen production. A factor of conversion efficiency between 65 and 70 percent allows the model to calculate hydrogen output quantitatively. The stored hydrogen has applications that enable electric power generation which supplies a different means to store energy. The models for energy storage through electrolyzers operate together with battery storage units to measure how different mediums cooperate during power distribution.

6) Combined Hybrid System Model

When the Combined Hybrid System model consolidates solar PV wind biomass and battery outputs into one system it acts as an integrated renewable energy platform. Available renewable energy supplies the current load requirements while extra energy goes into battery storage until the grid power covers shortages. The model reduces each power source into its energy production while determining system costs alongside CO_2 emission measurements. The integrative framework delivers an entire system which evaluates different renewable energy sources working together for better stability and sustainability goals.

D. Input Parameters and Assumptions

Right input data yields essential outcomes for accurate simulation results. These parameters emerge from historical data combined with literature analysis to include data points related to economic factors and technical aspects as well as environmental considerations.

1) Economic Parameters

Strategic economic factors take into account both grid power cost at 30 PKR per kilowatt-hour together with operation and maintenance costs from each energy platform. The operational price of biomass systems depends on fuel market data for processing and the costs to maintain solar panels and wind turbines need to be included too. The established parameters allow calculation of both operational expenses and unit energy cost (PKR/kWh) across the design configurations.

2) Environmental Parameters

Each energy source requires its emissions to be measured through emission factor analysis. The operational emissions of solar and wind systems remain almost non-existent in the analysis. Biomass systems generate emissions at the rate of 0.10 kg CO_2/kWh because of their fuel processing and combustion steps and grid power releases greater emissions through its fossil fuel-based power mix. All factors serve to evaluate the carbon footprint alongside emission intensity measurement (kg CO_2/kWh) for each system design.

3) Technical Parameters

Technical parameters encompass:

- Solar PV Efficiency: Typically 15–20%.
- Wind Turbine Capacity: Rated capacity values, for example, an equivalent of 30 MW in large-scale applications.
- Battery Capacity: Set at 3000 kWh with a 95% round-trip efficiency.
- Biomass Feed Rate: 2–3 tons per hour, with a lower heating value of 15 MJ/kg and a conversion efficiency of 28%.
- Electrolyzer Efficiency: Approximately 65–70%.
- Load Profiles: Hourly energy demand patterns, with peak loads around 1600 kW. These parameters are summarized in Table 1.

Table 1. Summary of Key Input Parameters

Parameter	Value/Range	Unit	Applicable Cases
Grid Power Cost	30	PKR/kWh	All (backup)
PV Efficiency	15–20	%	Cases 1, 2, 3, Combined
Wind Turbine Capacity	30	MW	Combined
Biomass Feed Rate	2–3	tons/h	Case 4, Combined
Biomass LHV	15	MJ/kg	Case 4, Combined
Biomass Conversion Efficiency	28	%	Case 4, Combined
Battery Capacity	3000	kWh	Cases 2, 3, Combined
Electrolyzer Efficiency	65–70	%	Case 3
CO_2 Emission Factor (Biomass)	0.10	kg CO_2/kWh	Case 4, Combined
Load Profile – Peak Hour	~1600	kW	All Cases

4) Assumptions

The following assumptions are made for modeling consistency:

- Historical averages are used for solar irradiance, wind speeds, and biomass feedstock availability.
- The battery operates with a constant efficiency (95% round-trip) and fixed capacity.
- Biomass feedstock is assumed to be available continuously during the operating hours.
- The electrolyzer operates under ideal conditions without degradation.
- The system implements a specific rule which gives preference to renewable energy supplies before activating storage measures then resorting to power from the electrical grid.

E. Simulation Procedure

1) Data Collection and Pre-Processing

Data acquisition for solar irradiance, wind speeds and biomass feed rates and load profiles is performed by using historical records supplemented with relevant literature studies. The simulation models receive processed data through normalization and unit conversion of historical records and literature-derived measurements arranged as one-hour time series.

2) Model Development

Dedicated models are developed for each configuration:

- Solar-Grid: Grid power supplements the electrical power produced by the PV model when solar irradiance does not produce enough electricity.

Volume:10 , No:1 ,pp.195-209
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- Solar-Battery: The PV model uses tracking of SoC through a battery model to save surplus energy which then serves the electrical load.
- Solar-Electrolyzer-Battery: The system integrates an electrolyzer model that transforms excess energy into hydrogen through the electrolysis process.
- Biomass: A simulated system produces electrical power from biomass streams through model construction based on thermodynamic equations combined with conversion ratios.
- Combined System: The combined power generation from separate renewable models creates a single power system which follows a fixed dispatch rule to meet end-user electricity requirements.

3) Execution and Data Collection

Simulations are run over a 24-hour period with one-hour time steps. During each time step, the model calculates:

- Power generated by each energy source.
- Battery charge/discharge cycles and SoC.
- Grid power consumption (if renewable generation is insufficient).
- Total energy generated, operational costs, and CO_2 emissions. The resulting time-series data are stored for analysis.

4) Data Visualization and Analysis

Output data are analyzed using graphical tools to generate plots and tables illustrating hourly performance. Key visualizations include:

- Time-series plots of power generation for each configuration.
- Battery SoC profiles.
- Comparative plots of operational costs and emissions. The visualations provide complete system performance assessment capabilities and enable side-by-side evaluation of standalone and collective configurations.

F. Performance Metrics

The performance of each configuration is assessed using three main categories:

1) Economic Metrics

During the simulation period the economic performance shows two points: total operational cost in PKR and cost of energy production in PKR/kWh. The established metrics enable researchers to assess which option results in lower costs when renewable resources are evaluated against standard grid power.

2) Environmental Metrics

The total CO_2 emissions (kg CO_2) combined with emission intensity (kg CO_2/kWh) represent the environmental impact measures. The examination establishes the carbon emissions ratio between various configurations.

3) Energy Efficiency Metrics

The actual output of electrical energy (kWh) serves as a basis to determine energy efficiency by observing how it matches the theoretical potential of renewable energy availability. The percentage ratio demonstrates how well the process transforms accessible energy into resulting power output. In the Combined Hybrid System the proportion of renewable energy within the overall power supply is determined.

G. Validation and Sensitivity Analysis

1) Model Validation

The simulation outcomes get validated through analysis of historical outputs from comparable renewable systems. The simulation models validate their accuracy by checking solar output and battery-related variables against actual measurement data from operating systems. The model parameters undergo changes to fix any detection of outlier values.

2) Sensitivity Analysis

The key parameters affecting the system inputs undergo sensitivity analysis through tests that adjust solar irradiance and wind speed levels and biomass feed and battery efficiency rates. System performance measurements regarding cost along with emissions and energy output help determine which factors most affect the system operation. The results of this analysis demonstrate both system stability and show the extent to which the solution reacts to technical and environmental uncertainties.

IV. RESULTS AND ANALYSIS

This section discusses simulation data evaluation of different renewable energy configurations. The standalone battery-operated systems Solar-Grid, Solar-Battery, Solar-Electrolyzer-Battery, and Biomass receive evaluation based on generated energy amounts together with operational expenses and environmental outcomes. The evaluation results demonstrate complete comparison between different configurations based on their ability to fulfill power requirements and show the combined advantages of renewable resource integration. A detailed evaluation and visual representation of simulation findings reveals vital trade-offs and trends which deliver actionable knowledge about sustainable power operations in combined energy systems.

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A. Case 1: Solar-Grid System Analysis

1) Solar Irradiance, DC Voltage, and DC Power Output

Irradiance values (W/m²) throughout the simulation period are shown in this visual depiction. The first and final parts start and end with peak irradiance levels that exceed 1000 W/m² while the middle section contains zero irradiance. The same pattern appears in the Vdc Mean (V) and Pdc Mean (kW) graphs which can be seen in the middle and bottom panels. The Vdc mean operates around 500 V steady during conditions of available irradiance which indicates a stable DC bus voltage. During periods of high insolation the Pdc mean stays at 250 kW yet it falls to zero at insolation zero moments before it regains its starting value upon insolation recovery. The solar array generates power at a direct relationship with incoming solar radiation which sustains steady DC voltage output and delivers strong power output when sunlight is strongest.

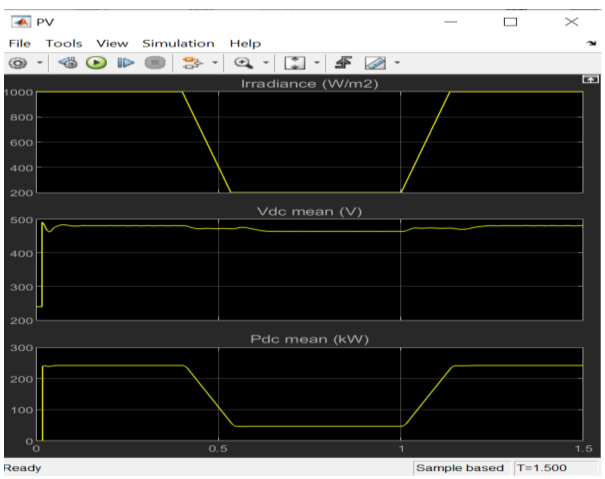

Fig. 1 Solar Irradiance, DC Voltage, and DC Power Output

2) Phase Voltage and Phase Current

The attached illustration shows voltage (V) and current (A) waveforms registered at the alternating current side. The measured Va trace functions like an ideal sinusoid with output amplitude that matches the operational parameters of the system. The maximum amplitude occurs during solar irradiance high periods at both ends of the simulation which maintains strong AC voltage output. At the moment of zero irradiance the inverter maintains a sinusoidal distribution pattern in voltage amplitude because of diminished power transfer. The Ia waveform tracks a smooth symmetrical pattern whose value matches power flow modifications. The inverter improves its current strength as solar power output grows to deliver higher amounts of energy between the system and its load and grid interface. The coherent Va and Ia waves indicate that the inverter maintains suitable control of AC power delivery while preventing any form of distortion.

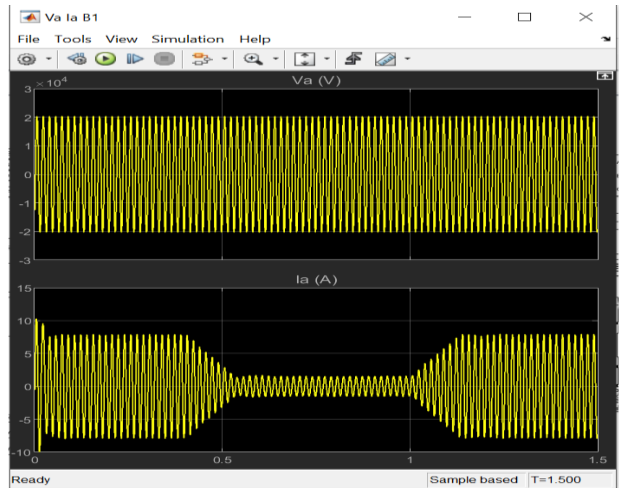

Fig. 2 Phase Voltage and Phase Current

3) Battery Power Output

This figure represents the P_B1 (kW) plot to show active power measurements. Power begins at 250 kW at the start because solar irradiance conditions are high at this point. The power measurements decrease sharply when the irradiance levels are zero but they return to their initial point as irradiance becomes available again. The measured power at the bus shows a direct correlation with solar availability because the system operates with high efficiency in transferring DC-generated power to the AC side during daylight hours. Power throughput through this configuration shows an identified direct relationship between solar input and P_B1 changes. The experimental data shows that the power system delivers available solar energy predictably as close as its original level when sunlight returns.

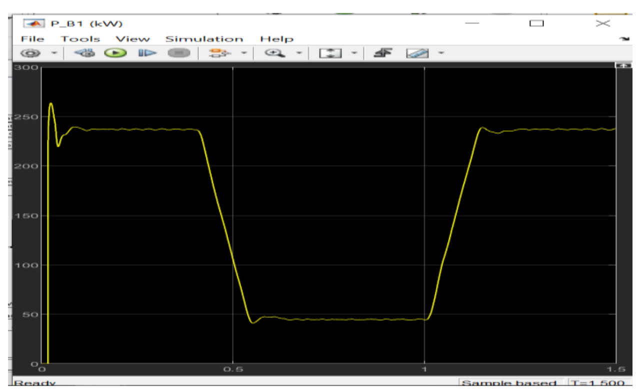

Fig. 3 Battery Power Output

B. Solar-Battery System Output Analysis

1) Solar Power Generation Profile

The solar-battery system generates power for a 24-hour simulation period which is displayed in the first output figure. The graphical output demonstrates a smooth power output pattern which starts by steadily increasing at morning times and reaches its maximum point at noon before decreasing after sunset. The system demonstrates its ability to collect solar power through the maximum power level reached during peak sun hours. Some variations in the plotted curves result from environmental factors that include temperature changes and photovoltaic system efficiency limitations. The power generation maintains a stable pattern throughout the day according to the overall pattern data.

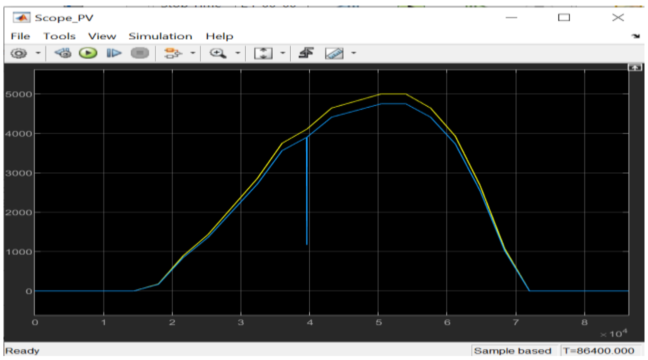

Fig. 4 Solar Power Generation Profile

2) Secondary Voltage Regulation

The secondary side RMS voltage monitoring is visualized in the second output figure of the inverter or transformer system. The measured voltage exists in the vicinity of 201V as the simulator operates without substantial voltage disturbances except brief moments. The system experiences these changes because of the changing load and the connected interaction between solar energy along with the battery system. Fluctuations in the system do not compromise stability because the system effectively controls voltage which preserves a continuous power flow. The solar-battery hybrid system proves its worth by keeping power distribution balanced across its specified voltage range despite changes in solar input strength.

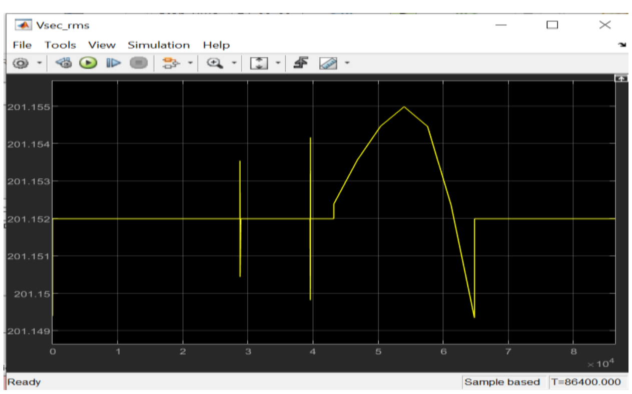

Fig. 5 Secondary Voltage Regulation

3) Power Flow and Battery Storage Dynamics

This output figure shows a complete summary of solar-battery system power flow variables which include photovoltaic panel power generation as well as secondary power usage together with load requirements and battery charging and discharging states and battery state-of-charge levels. The power generation by photovoltaic panels produces a bell-shaped curve which reaches maximum output during daytime hours before the decreasing trend sets in during evening hours according to solar irradiance levels. The management of secondary power distribution demonstrates an almost equivalent pattern to primary power distribution but its values shift slightly according to real-time energy balancing needs.

Daily electricity demand patterns result in the power load graph becoming unstable. The supply system draws its power mainly from solar resources when solar energy availability is high but falls back to battery power for periods of reduced solar irradiance. The battery's charging and discharging processes prove that solar power excess during daytime becomes available for usage when solar energy supply stops because of night or morning darkness. During peak solar hours the battery state-of-charge graph increases while it drops during the discharge period to supply the load demands.

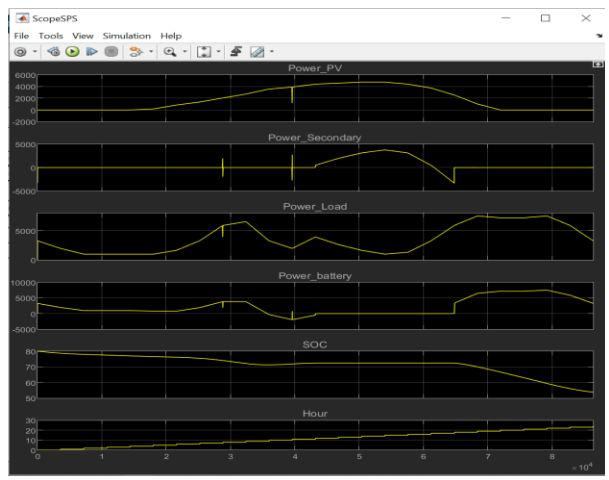

Fig. 6 Power Flow and Battery Storage Dynamics

The obtained results show the solar-battery system effectively stores and controls solar energy for maintaining uninterruptible power delivery. Solar power reliability improves through battery storage integration which stops the problem of intermittent energy access and lowers the need for grid power supply. The system demonstrates robust power delivery while maintaining stable voltage because of its ability to provide steady power flow which creates a sustainable energy management solution.

C. Case 3: Solar Energy Integrated with an Electrolyzer and Battery Storage

1) Power Distribution and Electrolyzer Performance

A clear illustration of power distribution occurs through output graphs between solar panels and the electrolyzer along with the storage system. The power output from solar panels behaves periodically through periods of sunlight becoming available. The electrolyzer achieves highest operational performance when solar radiation reaches its peak level to produce hydrogen storage. The storage system adjusts its power input and output in order to keep the entire system stable. The study results demonstrate that using an electrolyzer improves the energy storage capacity to effectively save excess solar energy for future consumption.

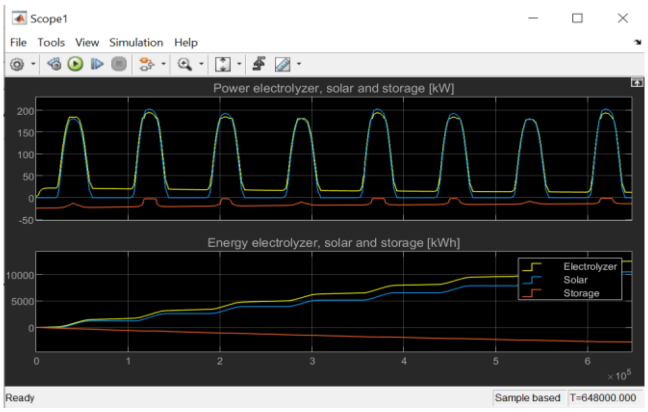

Fig. 7 Power Distribution and Electrolyzer Performance

2) Battery and Grid Voltage Regulation Hydrogen Production and Energy Storage Efficiency

The output voltages between the battery and grid system experience minimal fluctuation and show steady performance due to solar power supply changes. The battery charge decreases progressively throughout usage thus indicating its purpose of delivering power during low solar energy periods. By integrating the electrolyzer the system controls voltage by managing additional energy flows which prevents overvoltage conditions. The results show that the battery maintains a steady voltage output which solves voltage fluctuations problems.

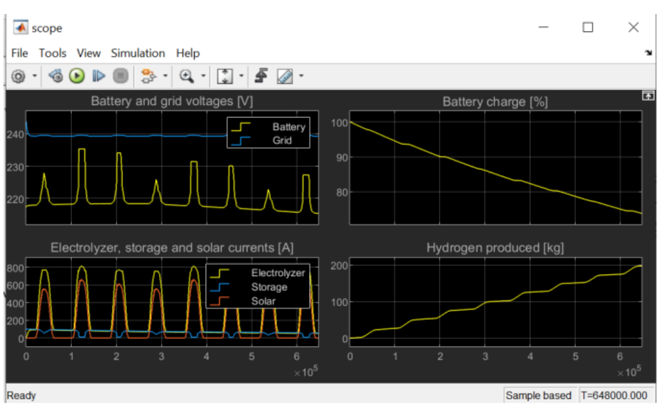

Fig. 8 Battery and Grid Voltage Regulation Hydrogen Production and Energy Storage Efficiency

The production of hydrogen depends on the amount of solar power that becomes available. The increasing solar power enables the electrolyzer to produce hydrogen which gets stored for future usage. The system demonstrates efficient power management because hydrogen production shows a continuous increase that proves proper utilization of surplus energy. The electrolyzer delivers optimal operational efficiency because it continuously transforms one kilowatt hour into each kilogram of produced hydrogen. The hydrogen storage capability proves that the system effectively preserves renewable energy as hydrogen thus decreasing the need for grid power.

3) Overall System Performance and Energy Management

The integrated system demonstrates superior energy management traits since it operates through dynamic operations between power sources and energy storage and usage functions. The peak solar energy collection enables efficient power usage so additional available energy drives hydrogen production followed by battery storage implementation. The implemented system achieves excellent results for energy security and sustainability through its ability to maintain uninterrupted power availability. The solar panel connection to the electrolyzer then the battery storage creates a system that optimizes energy operations while minimizing unnecessary energy loss.

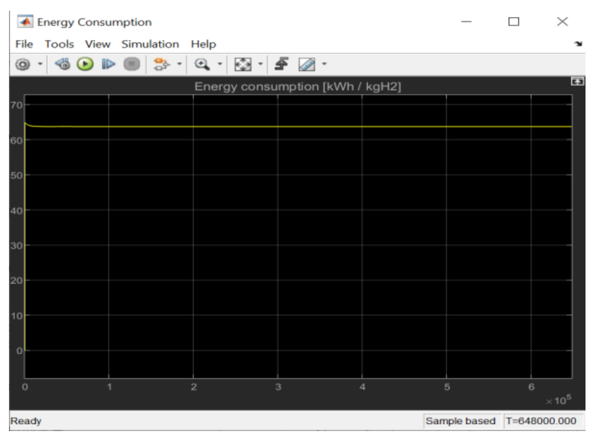

Fig. 9 Overall System Performance and Energy Management

The experimental results prove that coupling solar power with an electrolysis unit and battery storage improves both system reliability and reduces intermittent power supply while enabling sustainable long-term energy storage. The implemented power arrangement achieves excellent renewable power usage with stable system operation and top performance levels.

D. Case 4: Biomass Energy System

1) Biomass Power Plant Performance Metrics

The 24-hour simulation of the biomass power plant features its essential performance metrics in this initial picture. The installation runs at 3000 kW and achieves biomass conversion

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efficiency of 28% during the operation. The described power system generated a total amount of 67,783.71 kWh during the simulation period demonstrating its reliability as a stable power source. The energy output stability relies on maintaining biomass feed rate at 2.45 tons per hour and using 15 MJ/kg as the lower heating value of biomass. The measured CO_2 emissions from biomass combustion proceeded to 6778.37 kilogram. The operating expenses including fuel acquisition as well as operational upkeep reached 203,351.12 PKR.

```
=== BIOMASS POWER PLANT RESULTS (24-HOUR SIMULATION) ===
Plant Capacity (kW):                3000.00
Biomass Conversion Efficiency:      28.0%
Average Feed Rate (ton/h):          2.45
LHV of Biomass (MJ/kg):             15.00

Total Energy Generated (kWh):       67783.71
Total CO2 Emissions (kg):           6778.37
Total Operating Cost (PKR):         203351.12
```

Fig. 10 Biomass Power Plant Performance Metrics

2) Hourly Trends in Power Output, Emissions, and Cost

Power output together with operating costs and CO_2 emissions displays their variations over each hour in this depicted image. Power output sustains maximum capabilities at 3000 kW while feedstocks cause minimal changes throughout the hours. CO_2 emissions match the pattern of power generation because they increase as power output reaches its peak but decrease when power output falls. The operating costs fluctuate according to peak generation hours. The reported trends prove why organizations need to maximize fuel efficiency and improve combustion performance for lower production costs and reduced carbon emissions during reliable power supply operations.

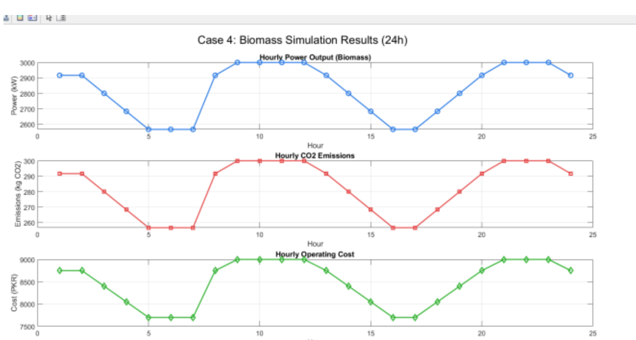

Fig. 11 Hourly Trends in Power Output, Emissions, and Cost

E. Combined Hybrid System Analysis

1) Performance Analysis of the Combined Hybrid System

The simulation ran the combined hybrid power system with solar power and wind power and biomass and battery storage for an entire day. Most of the 27,000-kWh total load demand was successfully managed by the system but it could not fulfill all requirements because it allowed 4,207.50 kWh of load to go unmet. Wind power delivered the maximum renewable energy through its 8,203.19-kWh production followed by biomass at 5,179.21 kWh while solar energy output amounted to 4,767.61 kWh. The grid electricity consumption amounted to 4,642.50 kilowatt-hours which supported the green energy generation when needed. The system operated under the influence of battery dynamics by charging 2,707.50 kWh while discharging 4,207.50 kWh before reaching a state of charge (SoC) of 0%. Operation costs summed to 151,192.69 Pakistani rupees and total emissions reached 3,945.05 kg during the period.

```
=== COMBINED HYBRID SYSTEM: SOLAR + WIND + BIOMASS + BATTERY ===
Total 24h Load (kWh):      27000.00
Unmet Load (kWh):         4207.50
---------------------------------------------
Solar Gen Used (kWh):     4767.61
Wind Gen Used  (kWh):     8203.19
Biomass Gen Used(kWh):    5179.21
Grid Consumption (kWh):   4642.50
---------------------------------------------
Battery Charge (kWh):     2707.50
Battery Discharge(kWh):   4207.50
Final Battery SoC (%):    0.00
---------------------------------------------
Total Emissions (kg):     3945.05
Total Cost (PKR):         151192.69
```

Fig. 12 Performance Analysis of the Combined Hybrid System

2) Graphical Interpretation of System Behavior

The present graphs explain the battry performance distribution patterns along with power fluctuations during a full 24-hour cycle. The top part of the graphic demonstrates which power generation sources provided electricity for changing power demand patterns. Wind and solar sources generated irregular power output while biomass together with the grid electricity system provided steady backup. The second graph tracks the battery operations by showing when batteries recharge during times of surplus generation then dispatch power to fulfill customer needs. The battery State of Charge begins at a higher value then lowers steadily until the end due to continuous discharging operations. The data demonstrates that battery storage provided critical balance to the system until it ran out of capacity which highlights the need for capacity growth.

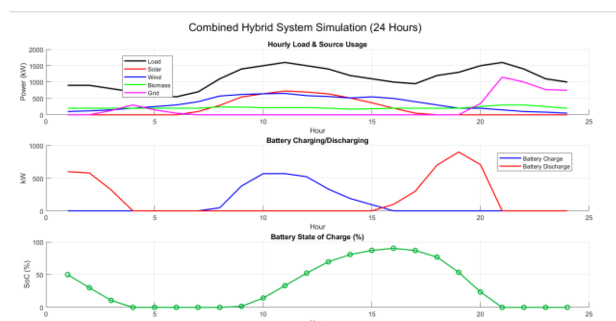

Fig. 13 Graphical Interpretation of System Behavior

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F. Sensitivity Analysis Results for Combined Hybrid System

1) Impact of Key Parameters on System Performance

An assessment of sensitivity analyzes which variations in different input parameters influence hybrid system performance. Power generation together with system cost and emissions levels and unmet load depend heavily on solar irradiance and wind speed values along with biomass availability and battery capacity.

Table 2. Effect of Solar Irradiance on System Performance

Solar Irradiance (W/m^2)	Solar Generation (kWh)	Battery SoC (%)	Unmet Load (kWh)	Total Cost (PKR)	Emissions (kg)
800	5500	30	5000	160000	4200
1000	7000	45	3500	150000	3950
1200	8500	60	2000	140000	3700

Table 3. Effect of Wind Speed on System Performance

Wind Speed (m/s)	Wind Generation (kWh)	Battery SoC (%)	Unmet Load (kWh)	Total Cost (PKR)	Emissions (kg)
5	6000	35	4500	155000	4100
7	8000	50	3000	145000	3850
9	9500	65	1500	135000	3600

Table 4. Effect of Biomass Availability on System Performance

Biomass Availability (%)	Biomass Generation (kWh)	Battery SoC (%)	Unmet Load (kWh)	Total Cost (PKR)	Emissions (kg)
50	4000	25	5500	165000	4300
75	5500	40	3000	150000	3950
100	7000	55	1500	140000	3650

V. DISCUSSION

Different hybrid energy system cases produce performance data that shows important information about renewable energy strengths and weaknesses and demonstrates the combined effect on reliability and cost and sustainability aspects. These results show how renewable power availability changes power output and storage operations and affects the operational efficiency of the system.

The combined hybrid system that combines solar power with wind power and biomass power includes storage batteries reveals superior reliability but shows 4207.50 kWh of unmet power needs indicating possible generation and storage capacity constraints. The combined output from wind generators and biomass generators exceeded the solar energy generation by providing 8203.19 kWh and 5179.21 kWh compared to 4767.61 kWh solar output. External power supply through the grid remained essential to meet the total electrical needs because 4642.50 kWh of energy came from outside the system. The controlling system used the battery as its primary balancing element by charging 2707.50 kWh while discharging 4207.50 kWh until it reached a complete zero state of charge. The combination of different energy sources led to a total emission release of 3945.05 kg while the system cost reached 151,192.69 PKR demonstrating the system's environmental and economic consequences.

The results of sensitivity tests demonstrate how alternating renewable energy conditions affect operational outcomes in the system. Changes in solar irradiance induced substantial changes to PV output because decreased irradiation levels reduced power production and created turbulence in DC voltage levels. The wind power supply systematically functioned yet its quantity fluctuated based on wind speed conditions. The biomass generator operated with reliability to sustain the power transmission during situations when other energy sources did not meet requirements. The battery state of charge shifted constantly during the day because it participated in load management but reached zero at the end which suggests increasing battery capacity to improve system reliability.

Different simulation results reveal that integrating renewable energy systems cuts down grid dependence but does not make independent power supply unnecessary. The function of the biomass generator in the system creates environmental emissions that remain present beyond standard power generation methods. The careful selection of renewable power generation types ensures both economic efficiency and operational reliability according to cost studies. System performance and efficiency in hybrid renewable energy systems requires thoughtful design methods together with suitable energy storage and real-time control approaches according to research results.

VI. CONCLUSION

The evaluation of the hybrid renewable energy system proves how different energy sources including solar power wind energy biomass and battery storage systems create more reliable and sustainable power operations. The analyzed system combination delivers better energy accessibility and cuts dependence on the power grid though it struggles to fulfill all operational needs based on unmet load data. The sensitivity analysis shows how different levels of renewable resources affect system performance and simultaneously determine system cost and emissions as well as energy efficiency.

The results confirm how crucial it is to enhance battery storage capabilities because this will help systems cope better with frequent changes in renewable energy output. Wind farms along with biomass facilities delivered substantial power to the system while decreasing the need for the grid and totaling lower carbon emissions although solar intermittency reduced energy supply stability. The cost evaluation demonstrates that hybrid control systems need an upfront purchase yet provide future operational savings alongside environmental sustainability features.

The project validated the successful design of a multi-source hybrid energy system which proves its capacity to sustainably generate power. Future research should prioritize improving control methods along with better energy storage systems as well as deploying hybrid systems in practical applications to enhance system operational stability and reliability.

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