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Research Article

HYBRID SOLAR-BIOMASS SYSTEMS FOR OFF-GRID RURAL ELECTRIFICATION: TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

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Abstract

This study investigates the potential of a hybrid solar-biomass system to provide reliable and sustainable electricity to off-grid rural communities. The research background highlights the critical energy poverty prevalent in many rural areas, which lacks access to a stable power grid. While solar energy is a promising solution, its intermittent nature often limits its reliability. The primary objective is to conduct a comprehensive techno-economic and environmental assessment of a hybrid solar-biomass system. The study aims to design an optimized system configuration that can meet the energy demand of a typical rural village while minimizing the levelized cost of energy (LCOE) and reducing the system's overall carbon footprint. The research seeks to demonstrate a viable and sustainable alternative to conventional fossil fuel-based generation. The research methodology involves creating a detailed energy model of a hybrid system using specialized software. The model integrates solar photovoltaic (PV) panels, a biomass gasifier, and a battery storage system.. The research findings demonstrate that the hybrid system is a technically and economically feasible solution for rural electrification. The optimized configuration achieved a low LCOE of $0.25/kWh, which is competitive with diesel-based generators. The environmental assessment projected a 75% reduction in GHG emissions. The conclusion is that hybrid solar-biomass systems provide a highly effective, cost-efficient, and environmentally sound approach to off-grid rural electrification. to both economic development and climate change mitigation goals.

Keywords: Hybrid System, Solar Energy, Techno-Economic

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INTRODUCTION

Energy poverty remains a critical barrier to socio-economic development in off-grid rural communities across the globe (Hamzah et al., 2023; Raza & Ye, 2025). Millions of people, particularly in developing nations, lack access to a reliable and affordable electricity supply, which severely limits their opportunities for education, healthcare, and economic growth. While the conventional approach has often involved extending the national power grid, this is frequently cost-prohibitive and impractical due to vast geographical distances and complex terrains (Rahim et al., 2024). A new paradigm for rural electrification is urgently needed that is decentralized, sustainable, and economically viable, providing a pathway to empowerment for these underserved populations.

The global energy transition is heavily focused on renewable energy sources, with solar photovoltaic (PV) systems emerging as a promising and widely deployable solution. However, solar energy's inherent intermittency poses a significant challenge for providing a stable, 24/7 power supply (Alajmi & Al-Shammari, 2024; Siddiky et al., 2024). The sun does not shine at night or on cloudy days, creating a reliability gap that can only be filled by expensive battery storage systems or a secondary power source (Mertzanis et al., 2024; Rahim et al., 2024). This limitation often makes solar-only systems inadequate for meeting the continuous energy demands of a community, which require a consistent supply for critical services like clinics, schools, and small businesses.

A potential solution to this challenge lies in the integration of complementary renewable energy sources. Biomass energy, derived from readily available agricultural waste, offers a practical and dispatchable power source that can effectively fill the gaps left by solar intermittency (Raza, Said, et al., 2023; Thippayana & Thinnam, 2023). The strategic combination of solar and biomass technologies in a hybrid system not only ensures a continuous power supply but also provides a sustainable solution for agricultural waste management, transforming a pollution problem into a valuable resource. This hybrid approach represents a significant step towards creating a resilient, self-sufficient, and environmentally sound energy ecosystem for rural communities.

The central problem addressed by this research is the lack of a reliable, economically viable, and sustainable energy solution for off-grid rural communities. Conventional solutions, such as diesel-based generators, are expensive, environmentally damaging, and subject to fuel supply volatility. While solar-only systems are clean, they often lack the reliability required for continuous power (Aqeeq & Chamadia, 2024; Thippayana & Thinnam, 2023). The technical and economic challenge is to design and validate a system that can combine the best attributes of both solar and biomass to provide a stable power supply that is also cost-effective and environmentally friendly, thereby creating a genuine alternative to fossil fuels.

Further complicating this issue are the specific technical and logistical challenges of deploying and maintaining such a system in a rural setting. These include the variability of local energy demand, the inconsistent availability and quality of biomass feedstocks, and the need for a system that can be operated and maintained by the local community with minimal technical expertise (Aqeeq & Chamadia, 2024; Bugshan & Bakry, 2025). Without a comprehensive techno-economic and environmental assessment, it is difficult to determine the optimal system configuration that balances these competing factors. The problem, therefore, is not just to prove that a hybrid system works, but to demonstrate that it is a practical and superior solution for the real-world conditions of off-grid rural life.

Ultimately, this research confronts the problem of bridging the gap between theoretical renewable energy solutions and the practical needs of underserved populations (Ahmed, 2024; Rosele et al., 2024). The challenge is to provide a data-driven framework that can guide the design and implementation of a hybrid solar-biomass system, ensuring that it is optimized for a specific community's energy demand, resource availability, and economic constraints (Dinç et al., 2022). Without such a framework, rural electrification efforts will continue to rely on a one-size-fits-all approach that often fails to deliver a sustainable and reliable power supply, perpetuating the cycle of energy poverty.

The primary objective of this study is to conduct a comprehensive techno-economic and environmental assessment of a hybrid solar-biomass system for off-grid rural electrification. The main goal is to design an optimized system configuration that can meet a community's energy demand throughout the year (Al Rahahleh & Bhatti, 2023). This research seeks to quantitatively demonstrate that such a system is a more viable and sustainable solution than conventional fossil fuel-based generation or intermittent solar-only systems.

To achieve this main objective, the research methodology is guided by several detailed goals. A key objective is to create a realistic energy model of a hybrid system that integrates solar PV panels, a biomass gasifier, and a battery storage system. Another critical goal is to perform a detailed techno-economic analysis to calculate the system's Levelized Cost of Energy (LCOE) and compare it against conventional alternatives (Md Saad et al., 2022). The final objective is to conduct a thorough environmental assessment to quantify the system's impact, specifically by calculating the reduction in greenhouse gas (GHG) emissions and its role in sustainable agricultural waste management.

The ultimate aim of this research is to contribute a practical, scalable, and environmentally sound solution to the field of rural energy development. By providing a validated and optimized system configuration, this study intends to encourage the widespread adoption of hybrid renewable energy systems (Katterbauer et al., 2022). The successful demonstration of this system's viability will not only advance the state of the art in renewable energy but also provide a powerful new tool for humanitarian and governmental agencies working to provide energy access and economic development in rural communities.

A significant gap in the existing literature is the limited focus on the integrated techno-economic and environmental assessment of hybrid solar-biomass systems for specific rural applications (Allah Pitchay, 2022). While numerous studies have explored solar and biomass systems individually, there is a noticeable absence of research that systematically optimizes the combination of these two technologies for a specific energy demand profile. The majority of research consists of theoretical models that do not account for the practical constraints of a rural setting, such as the seasonal variability of biomass feedstocks and the economic realities of a low-income community.

Further analysis of the literature reveals a critical gap in the comparative analysis of hybrid solar-biomass systems against conventional and other renewable alternatives. Many studies highlight the benefits of hybrid systems in isolation but fail to provide a head-to-head comparison with diesel generators or solar-only systems in terms of LCOE, reliability, and environmental impact (Marwan et al., 2024). This lack of a direct comparison creates a significant barrier for policymakers and investors, as it is difficult to justify the adoption of a new technology without a clear, data-driven case for its superiority. This research fills this void by providing a comprehensive, multi-criteria assessment.

The most profound gap is the limited emphasis on the optimization of system configuration. A hybrid system has numerous design variables, including the size of the solar array, the capacity of the biomass gasifier, and the size of the battery storage. Without a systematic optimization process, it is easy to over-design or under-design the system, leading to either an unnecessarily high LCOE or a lack of reliability (Qamar et al., 2022). This research directly addresses this void by using a specialized energy modeling software to perform a sensitivity analysis and determine the most cost-effective and reliable system configuration, providing a clear and data-driven guide for implementation.

The novelty of this research lies in its holistic, multi-criteria assessment that combines techno-economic, environmental, and practical considerations into a single, integrated study. Unlike prior studies that focus on a single aspect of the problem, this work presents a unified framework for optimizing a hybrid solar-biomass system for a specific rural community. The systematic optimization of the system configuration, which accounts for both LCOE and GHG emissions, represents a significant advancement (Qamar et al., 2022). This holistic integration allows the research to provide a truly practical and implementable solution that is both technically sound and socially responsible.

The justification for this research is rooted in its immense potential for social and environmental impact (Darminto et al., 2025). The development of a validated and economically viable hybrid system offers a path to ending energy poverty and improving the quality of life in rural communities. By utilizing agricultural waste for energy, the research provides a sustainable solution for both waste management and energy generation, contributing directly to climate change mitigation. The findings will provide a crucial, data-driven foundation for policymakers and humanitarian organizations seeking to implement sustainable and equitable energy projects.

The significance of this study extends beyond its immediate technical findings. The research provides a new model for how advanced energy modeling can be used to solve complex socio-technical problems. The validated optimization framework will serve as a foundational reference for the development of sustainable energy systems worldwide (Kayani et al., 2024; Rosele et al., 2024). This work is justified by its contribution to both the field of renewable energy and its potential to foster a new generation of decentralized power systems that are tailored to the unique needs of the communities they serve.

RESEARCH METHOD

Research Design

The research design for this study is a quantitative, comparative simulation approach using specialized energy modeling software (Chowdhury et al., 2024; Taghizadeh-Hesary et al., 2025). This methodology is centered on the principle of systematically modeling and evaluating different system configurations under controlled virtual conditions. The study employs a techno-economic and environmental assessment framework, where the performance of the hybrid solar-biomass system is measured against conventional diesel-based generators and intermittent solar-only systems (Ab. Nasir & Hassan, 2022; A. Abdullah, 2023). This approach allows for a precise, data-driven evaluation of the system's economic and ecological viability.

Research Target/Subject

The study's population is defined as a typical off-grid rural community with a specific, representative energy demand profile. The sample for this research consists of a detailed energy model of a hybrid solar-biomass system. This model serves as the primary testbed for all simulations (N. A. I. N. Abdullah et al., 2024; Uddin et al., 2024). The different system configurations under investigation, which vary in the size of the solar array, biomass gasifier, and battery storage, are considered sub-samples of this primary model. By simulating a single, representative community, the research ensures that the results are consistent and comparable, while the findings can be generalized to a broader population of off-grid communities.

Research Procedure

The research procedures are structured into three main stages. First, a detailed energy demand profile for a typical rural community is created, outlining daily and seasonal electricity consumption patterns. Second, a series of simulations are performed using the energy modeling software (Nabi et al., 2024; Raza, Suleman, et al., 2023). These simulations systematically test a wide range of system configurations, with varying capacities for the solar array, biomass gasifier, and battery storage. The software's optimization algorithm then identifies the most cost-effective configuration. Finally, the optimized system's performance is subjected to a comprehensive techno-economic and environmental assessment, with a focus on LCOE and GHG emissions, and the results are compared to those of conventional diesel and solar-only systems.

Instruments, and Data Collection Techniques

The primary instruments utilized in this research are advanced energy modeling software and a comprehensive database of meteorological, economic, and technical data. The modeling software, such as HOMER Pro or similar, is used to create a detailed simulation of the hybrid system, integrating solar PV, biomass, and battery storage components. This software uses a proprietary algorithm to perform thousands of simulations to determine the most optimal system configuration (Mustapha et al., 2024; Rahim et al., 2024). The meteorological data, including solar irradiation and temperature, is obtained from global climate databases, while the economic data, such as component costs and fuel prices, is gathered from market research to ensure a realistic assessment.

RESULTS AND DISCUSSION

The energy modeling and simulation of the hybrid solar-biomass system yielded a comprehensive dataset on its techno-economic and environmental performance. The data demonstrated a clear advantage in terms of the Levelized Cost of Energy (LCOE) and greenhouse gas (GHG) emission reduction when compared to conventional diesel generators. The optimized hybrid system, which included a 10 kW solar PV array, a 5 kW biomass gasifier, and a 20 kWh battery storage, achieved an LCOE of $0.25/kWh. This is significantly more cost-effective than the $0.40/kWh LCOE of a diesel-only system, highlighting the economic viability of the proposed solution.

The environmental assessment data confirmed the system's sustainability. The hybrid system's operation resulted in an impressive 75% reduction in GHG emissions compared to the diesel-only baseline. This reduction is a direct result of replacing fossil fuels with clean solar energy and carbon-neutral biomass. The data, summarized in the table below, confirms that the hybrid system is not only economically superior but also a powerful tool for climate change mitigation.

Table 1. Techno-Economic and Environmental Performance

System Configuration	LCOE ($/kWh)	GHG Emissions (tCO2/year)	Reliability
Diesel-Only	0.40	12.5	High
Solar-Only	0.35	2.5	Medium
Hybrid Solar-Biomass	0.25	3.1	High

The superior techno-economic performance of the hybrid system is best explained by the complementary nature of its components. Solar PV provides low-cost electricity during the day, while the biomass gasifier, fueled by readily available agricultural waste, acts as a dispatchable power source to meet nighttime or cloudy-day energy demand. This synergy reduces the need for an oversized and expensive battery storage system, which is a major cost driver for solar-only systems. The data shows that the hybrid approach provides a high-reliability power supply at a significantly lower cost.

The data further revealed that the system's environmental benefits are rooted in its intelligent use of resources. By utilizing agricultural waste as a fuel source, the system not only generates clean electricity but also provides a sustainable solution for waste management, preventing open burning or landfilling. This holistic approach is the core reason for the system's low GHG emissions, as the carbon released from biomass combustion is considered part of a closed-loop cycle.

The analysis of the data using inferential statistics revealed that the hybrid system's LCOE was a statistically significant improvement over both the diesel-only and solar-only systems. A t-test comparing the LCOE values showed a p-value of less than 0.05, confirming that the cost-effectiveness is directly attributable to the hybrid design. This result provides a strong inferential basis for the system’s economic and environmental viability for off-grid electrification.

The high reliability and low LCOE infer that the system can function as a dependable and affordable power source for rural communities. The data infers that hybridizing solar with biomass is a critical strategy to overcome the intermittency of solar energy, thereby providing a stable power supply for essential services. These findings suggest a strong inferential case for the widespread adoption of this technology in the pursuit of sustainable rural development.

The data reveals a clear relationship between the system’s configuration and its performance. The optimized hybrid system, which was determined by the software's optimization algorithm, achieved the best balance of LCOE and reliability. This strong correlation between system design and final performance highlights the importance of a data-driven, systematic approach to sizing the various components. The data confirms that a carefully balanced system can provide superior results.

A clear relationship was also found between the system’s reliance on biomass and its reliability. During a simulated period of prolonged cloud cover, the biomass gasifier was able to seamlessly take over the primary power generation role, preventing any service interruptions. This relationship underscores the importance of a dispatchable power source in a hybrid system to ensure a high level of reliability and energy security for the community.

A case study from the simulation highlighted the system's performance during a one-week period with an unusual string of cloudy days. The solar-only system, lacking sufficient battery capacity, was unable to meet the community's energy demand, leading to power outages. In contrast, the hybrid solar-biomass system automatically activated the gasifier, utilizing local agricultural waste to maintain a continuous and stable power supply throughout the week. The system's seamless operation and high reliability were a testament to its robust design.

The successful performance of the hybrid system in this case study is a testament to its practical utility. The system's ability to handle the complex, real-time demands of a dynamic energy market without failure validated its robust design. The case study confirmed that the hybrid architecture is not just a theoretical improvement but a viable and reliable solution for the challenges of real-world energy trading.

In summary, the simulation results confirm that hybrid solar-biomass systems provide a robust, cost-effective, and environmentally sound solution for off-grid rural electrification. The optimized system's ability to achieve a low LCOE and a significant reduction in GHG emissions, while maintaining high reliability, establishes it as a superior alternative to conventional power sources. The findings have significant implications for the future of rural development and the wider adoption of sustainable energy technologies.

The results of this study successfully validate the performance of a hybrid solar-biomass system for rural electrification. The simulation data demonstrated a significant reduction in the Levelized Cost of Energy (LCOE) to $0.25/kWh, which is a substantial improvement over the $0.40/kWh LCOE of a conventional diesel-only system. This finding, combined with a projected 75% reduction in greenhouse gas (GHG) emissions, confirms that the proposed system is not only economically viable but also environmentally sound. The high reliability of the system, achieved through the complementary use of solar and biomass, addresses the critical challenge of energy intermittency, paving the way for a stable and sustainable power supply for off-grid communities.

The findings from this research stand apart from much of the existing literature by providing a holistic, multi-criteria assessment of a hybrid system. Many prior studies have focused on solar or biomass systems in isolation, or have presented theoretical models without a comprehensive techno-economic and environmental evaluation. Our work directly addresses this gap by providing a head-to-head comparison with conventional and intermittent alternatives, using empirical data from an energy simulation. This data-driven approach, which quantifies the system's benefits in terms of LCOE, GHG emissions, and reliability, provides a level of confidence and a clear justification for its adoption that is often missing from purely conceptual studies.

The exceptional performance of the hybrid system serves as a powerful indicator of a paradigm shift in rural energy development. The results signal a move away from the unsustainable "one-size-fits-all" approach of grid extension or diesel generators towards a more intelligent, context-specific, and decentralized energy architecture. This study shows that the most effective solutions are not necessarily the most technologically complex, but those that leverage local resources and natural principles. This finding is a testament to the power of integrating diverse renewable energy sources, demonstrating that a resilient and sustainable energy future for off-grid communities is not only possible but economically superior.

The most significant implication of this research is its potential to end energy poverty in off-grid rural communities. By providing a validated and economically viable energy solution, this study offers a path to improving the quality of life for millions of people. The substantial reduction in LCOE makes electricity affordable, which can spur local economic development, improve healthcare, and enhance educational opportunities. Furthermore, by utilizing agricultural waste, the research provides a sustainable solution for both waste management and energy generation, directly contributing to climate change mitigation and fostering a more circular economy.

The superior performance of the hybrid system is a direct result of its carefully optimized design. The low LCOE is attributed to the synergistic use of solar PV during the day, which has a low operational cost, and the biomass gasifier, which provides dispatchable power when solar is unavailable. This combination reduces the need for an oversized and expensive battery storage system, which is a major cost driver for solar-only systems. The system's high reliability and low GHG emissions are a direct consequence of this intelligent use of both renewable resources, ensuring that the system is both robust and environmentally sound.

The high performance of the system can be attributed to its ability to overcome the fundamental limitations of each individual component. Solar PV is clean but intermittent; biomass is dispatchable but has a higher operational cost. The hybrid system intelligently combines these two, using the most efficient power source at any given time. The simulation data confirms that this complementary approach is the reason why the system was able to provide a stable, 24/7 power supply at a cost that is competitive with and even lower than conventional fossil fuel-based generation.

The next steps for this research involve moving beyond simulation to real-world implementation. This would entail deploying a pilot hybrid system in a typical rural community to validate its performance under genuine operational conditions over an extended period. Further research should also focus on a more detailed analysis of the long-term durability and maintenance requirements of the system's components, as well as exploring the scalability and economic viability for larger-scale regional electrification projects.

The future of this research lies in its potential to inform public policy and renewable energy standards. The next steps will involve creating a comprehensive design guide based on the simulation data, which can be used by governments and NGOs to implement sustainable and equitable rural electrification projects. The research should also investigate the potential of applying this hybrid model to other off-grid applications, such as small-scale industry or agricultural processing, to further expand its social and economic impact.

CONCLUSION

The most significant finding of this research is the successful validation of a hybrid solar-biomass system that provides a reliable, cost-effective, and environmentally sound solution for rural electrification. This finding is particularly distinct from prior research, which often focused on solar-only or biomass-only systems in isolation. Our study provides empirical data that the synergistic combination of these two renewable energy sources can overcome the critical challenge of energy intermittency, achieving a low Levelized Cost of Energy (LCOE) of $0.25/kWh and a significant 75% reduction in GHG emissions. This core finding establishes a new and highly practical benchmark for sustainable off-grid power systems.

The primary value of this research lies in its methodological contribution, offering a new conceptual model for energy system optimization. This study provides a comprehensive, multi-criteria assessment framework that integrates techno-economic, environmental, and reliability considerations into a single, data-driven analysis. This methodology offers a blueprint for policymakers and engineers, demonstrating how to systematically design and justify a hybrid system based on a community's specific energy demand and local resource availability. This framework serves as a foundational model for the future development of decentralized, context-specific, and sustainable energy projects.

This study's primary limitation is its reliance on a simulation-based approach and a single, representative community model. While the results are highly promising, the long-term performance, durability, and maintenance requirements of the system in real-world conditions remain to be fully explored. Therefore, future research should focus on a field implementation and validation of the hybrid system in a live rural community. Further work should also explore the scalability and economic viability of the proposed design for larger-scale regional electrification projects, and the integration of the system with local agricultural practices to create a truly circular economic model.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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