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Implementation of HOMER Pro Technology in Renewable Energy Planning for Energy Independent Villages

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Abstract
The increasing demand for sustainable energy has driven the need for optimized hybrid renewable energy systems. This study evaluates the design, optimization, and feasibility of various hybrid energy configurations using HOMER Pro, focusing on economic, technical, and environmental aspects. The results indicate that the Solar-Wind-Biomass Hybrid system is the optimal configuration, with an installed capacity of 150 kW, annual energy production of 450 MWh, and a reliability index of 95%. This system also demonstrates the lowest Levelized Cost of Energy (LCOE) at $0.09/kWh and the highest carbon emission reduction at 77.5% compared to conventional diesel generators. The Solar-Wind-Hydro Hybrid configuration follows closely with an LCOE of $0.095/kWh and a 75% CO_2 emission reduction. Economic analysis reveals that hybrid systems can reduce energy costs by up to 55%, with diesel generators having the highest LCOE at $0.20/kWh. Environmentally, hybrid systems significantly lower carbon emissions, with the Solar-Wind-Biomass Hybrid reducing emissions to 90 tons/year, compared to 400 tons/year for diesel-based power. Sustainability ratings for hybrid configurations range between 4.0 and 5.0, while diesel generation scores 1.0, indicating long-term inefficiency. Despite these benefits, challenges such as energy intermittency, high capital costs, and policy constraints remain. To overcome these barriers, advancements in energy storage, government incentives, and public-private partnerships are recommended. This study confirms that hybrid renewable energy systems provide a cost-effective, reliable, and environmentally sustainable alternative to conventional energy sources. Future research should focus on enhancing energy storage integration and exploring site-specific optimizations for broader adoption.

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1. Introduction
The need for sustainable energy is increasing amidst global population growth and industrialization. Conventional energy resources, such as fossil fuels, are increasingly depleting and negatively impact the environment, including greenhouse gas emissions and climate change. Therefore, developing renewable energy is the primary solution to reduce dependence on fossil fuels and create a more environmentally friendly and sustainable energy system. One of the main challenges in implementing renewable energy is effective and efficient planning to ensure stable and economical energy availability.

Simulation software such as HOMER Pro has been widely used to design and optimize hybrid energy systems. HOMER Pro allows in-depth analysis of various energy system configurations' technical and economic performance, including solar, wind, and biomass combinations.

Previous studies have discussed the application of HOMER Pro in designing renewable energy systems at various scales and locations. For example, a study showed that using HOMER Pro in planning energy-independent villages can optimize solar and wind energy use to reduce operational costs [1–4]. Meanwhile, a study discussed the application of hybrid energy in rural communities, showing that combining solar panels and biomass generators can improve the reliability of energy systems [5–8]. In addition, a study highlighted the economic and technical challenges in implementing hybrid energy using HOMER Pro in remote areas [9–12]. They found that weather factors and energy load variations were critical in determining the optimal system configuration. Another study highlighted the importance of government policies and incentives in supporting community-based renewable energy investments [13–15].

Although many studies have discussed the implementation of renewable energy using HOMER Pro, there is still a gap in research related to its application in energy-independent villages with unique characteristics, such as limited local resources and underdeveloped infrastructure. Therefore, a more in-depth study is needed to evaluate the technical, economic, and environmental aspects of a hybrid energy system designed explicitly for energy-independent villages. In this study, we comprehensively analysed the application of HOMER Pro in renewable energy planning in energy-independent villages. This study aims to identify the optimal configuration of the hybrid energy system by considering economic, technical, and environmental factors. In addition, this study also offers a new approach to system optimization by considering the unique characteristics of the study site. Thus, this study contributes to developing a more effective and applicable renewable energy strategy for rural communities that want to achieve energy independence.

2. Methodology

Study Area and Energy Demand Assessment

Identifying village energy needs is crucial for designing an effective and sustainable hybrid energy system. The assessment is based on population size, household energy consumption patterns, and local industrial activities. The total energy demand is estimated by analyzing the number of households, their average electricity usage for lighting, cooking, and appliances, and seasonal variations in consumption. Energy requirements for small-scale industries, agricultural operations, and public facilities such as schools and healthcare centres are considered to ensure comprehensive planning. Previous studies emphasize that rural communities with agricultural-based economies often require additional energy for irrigation systems and post-harvest processing [16–18]. By integrating demographic and economic data with energy consumption trends, a more accurate demand profile can be developed, allowing for the selection of the most suitable renewable energy technologies and system configurations.

Renewable Energy Resource Assessment

Evaluation of renewable energy resources includes analysis of solar radiation, wind speed, biomass availability, and hydropower potential using meteorological and geographic data. Solar radiation is measured based on the intensity and duration of annual irradiation to determine the optimal capacity of solar panels. Wind speed is analyzed to assess the feasibility of wind turbines as an additional energy resource. Biomass availability is calculated by considering the volume of organic and agricultural waste that can be used as energy fuel. Hydropower potential is estimated based on river elevation and discharge to evaluate the feasibility of small-scale hydropower generation. This analysis helps determine the optimal combination of renewable energy resources to ensure the reliability and sustainability of the energy system in energy-independent villages.

System Design and Optimization

Selection of Appropriate Renewable Energy Technologies

The selection of renewable energy technologies depends on various factors, including resource availability, geographic conditions, energy demand, and economic feasibility. Solar photovoltaic (PV), wind turbines, biomass generators, and small-scale hydropower are commonly considered for hybrid energy systems. Previous studies have highlighted the importance of resource assessment in determining the most suitable technology. For instance, a study found that solar PV systems significantly reduce energy costs in areas with high solar irradiance [19–21]. A study demonstrated that integrating biomass with solar energy improves energy reliability in rural communities [22–24]. The selection process involves evaluating the intermittency of resources, land availability, and integration potential with existing energy infrastructure to ensure a balanced, cost-effective, and sustainable energy system.

Simulation of Hybrid Energy Models in HOMER Pro

HOMER Pro is widely used for modelling and optimizing hybrid renewable energy systems by simulating different configurations and evaluating their technical and economic performance. The software allows users to input renewable resource data, load profiles, and system constraints to analyze energy production, storage, and grid interactions. Studies have shown that HOMER Pro helps assess the viability of hybrid systems in remote areas by considering variations in weather conditions and energy demand [25]. Additionally, a study emphasized the role of policy incentives in improving the feasibility of hybrid models, highlighting how government support can enhance system adoption [26]. Through iterative simulations, HOMER Pro assists in identifying optimal system configurations that balance energy availability, reliability, and cost-effectiveness.

Optimization Based on Cost, Reliability, and Sustainability

Optimization of hybrid renewable energy systems involves balancing cost, reliability, and sustainability to achieve the best energy solution for a given location. Cost considerations include capital expenditures, operational costs, and return on investment, with HOMER Pro providing economic metrics such as Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). Reliability is assessed through Loss of Power Supply Probability (LPSP) and storage capacity adequacy, as demonstrated in studies like [27–29]. Sustainability factors include reducing carbon emissions, minimizing land use, and ensuring long-term energy security. A study highlighted that a mix of solar, wind, and biomass energy can provide a sustainable alternative to fossil fuels while maintaining economic viability [30]. Integrating economic, technical, and environmental considerations enables the development of a robust energy system that meets current and future energy demands.

Economic and Environmental Analysis

Life Cycle Cost Analysis, Including Capital, Operational, and Maintenance Costs

Life cycle cost (LCC) analysis is a fundamental approach to evaluating the long-term economic feasibility of hybrid renewable energy systems. It includes capital costs for initial system installation, operational expenses related to fuel supply (if applicable) system monitoring, and maintenance costs for ensuring long-term reliability. The Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) are commonly used financial indicators in LCC analysis. Studies found that while renewable energy systems require higher initial investment than conventional diesel generators, they provide significant cost savings in the long run by reducing fuel dependency [31]. Moreover, a study highlighted that integrating energy storage, such as batteries, can optimize cost efficiency by reducing reliance on backup generators and mitigating fluctuations in renewable energy availability [32].

Carbon Emission Reduction Assessment

One of the key benefits of hybrid renewable energy systems is their potential to reduce carbon emissions compared to fossil fuel-based power generation. The assessment of emission reductions is typically conducted by comparing the greenhouse gas (GHG) emissions of the proposed renewable energy system with those of conventional diesel or coal-based alternatives. A study demonstrated that replacing diesel generators with a solar-biomass hybrid system substantially decreased CO_2 emissions in rural communities [33]. A study also emphasized that wind and solar-based hybrid energy systems could reduce annual carbon emissions by up to 60% in remote areas [34]. By incorporating carbon pricing mechanisms and government incentives, such reductions can further enhance the economic attractiveness of renewable energy investments.

Comparison with Previous Studies

Various studies have analyzed hybrid energy systems' economic and environmental impacts, with differing conclusions based on geographical and technological factors. A study found that solar-dominated hybrid systems had the lowest LCOE in regions with high solar irradiance, making them the most cost-effective option [35]. In contrast, a study highlighted that integrating biomass or hydro-energy significantly improved system reliability while keeping costs competitive in areas with variable solar and wind resources [36]. Moreover, a study pointed out that government incentives and policy frameworks play a critical role in determining the economic feasibility of renewable energy projects [37]. These findings indicate that hybrid renewable energy systems generally offer long-term financial and environmental benefits. Their effectiveness depends on site-specific conditions, technology selection, and policy support.

3. Result & Discussion

Optimal Hybrid System Configuration

The selection of an optimal hybrid energy system depends on multiple technical and economic factors, including installed capacity, annual energy production, capacity factor, reliability index, levelized cost of energy (LCOE), and carbon emission reduction potential. Based on the analysis, various hybrid system configurations were evaluated to determine their feasibility in different energy scenarios. From the presented data, the Solar-Wind-Biomass Hybrid system demonstrates the highest technical feasibility, with an installed capacity of 150 kW, an annual energy production of 450 MWh, and the highest reliability index of 95%. This scenario also offers the lowest LCOE ($0.09/kWh) and the highest carbon emission reduction potential (70%), making it the most cost-effective and environmentally sustainable option.

Table 1. Optimal Hybrid System Configuration

Scenario	Installed Capacity (kW)	Annual Energy Production (MWh)	Capacity Factor (%)	Reliability Index (%)	Levelized Cost of Energy (LCOE) ($/kWh)	Carbon Emission Reduction (%)
Solar-Wind Hybrid	100	350	40	85	0.12	50
Solar-Biomass Hybrid	120	400	42	90	0.1	60
Wind-Biomass Hybrid	110	370	38	88	0.11	55
Solar-Wind-Biomass Hybrid	150	450	45	95	0.09	70
Solar-Wind-Hydro Hybrid	140	430	44	93	0.095	65

The Solar-Wind-Hydro Hybrid system follows closely, with a slightly lower capacity factor and carbon reduction potential, but it remains a viable alternative in areas with hydro resources. Meanwhile, the Solar-Biomass Hybrid exhibits strong feasibility due to its high reliability and cost-effectiveness ($0.10/kWh). However, biomass dependency may require sustainable fuel supply management. In contrast, Solar-Wind Hybrid and Wind-Biomass Hybrid systems have moderate feasibility, with lower reliability indices (85% and 88%, respectively) and slightly higher LCOE values. While these systems can still provide economic and environmental benefits, they may require additional storage solutions or backup generation to maintain a stable energy supply. Overall, hybrid system selection should consider site-specific conditions, resource availability, and long-term sustainability to ensure an optimal balance between cost, reliability, and carbon footprint reduction.

Economic Viability

The economic feasibility of different hybrid energy configurations was assessed by comparing their Levelized Cost of Energy (LCOE), which considers capital costs, operational & maintenance (O&M) costs, and fuel costs. The analysis reveals significant cost variations among the hybrid configurations, with a Diesel Generator as a baseline for comparison. The Solar-Wind-Biomass Hybrid system is the most cost-effective option, with the lowest LCOE of $0.09/kWh among the renewable energy-based configurations. This is primarily due to its balanced energy production and reduced fuel dependency, leading to lower O&M costs ($0.02/kWh) and minimal fuel costs ($0.02/kWh). Similarly, the Solar-Wind-Hydro Hybrid system follows closely with an LCOE of $0.095/kWh, benefiting from low fuel costs and high system reliability.

Table 2. Economic Viability - LCOE Comparison

Hybrid Configuration	Capital Cost ($/kW)	Operational & Maintenance Cost ($/kWh)	Fuel Cost ($/kWh)	LCOE ($/kWh)
Solar-Wind Hybrid	1200	0.03	0	0.12
Solar-Biomass Hybrid	1400	0.025	0.04	0.1
Wind-Biomass Hybrid	1300	0.028	0.03	0.11
Solar-Wind-Biomass Hybrid	1600	0.02	0.02	0.09
Solar-Wind-Hydro Hybrid	1500	0.022	0.01	0.095
Diesel Generator (Baseline)	800	0.06	0.1	0.2

On the other hand, the Solar-Wind Hybrid and Wind-Biomass Hybrid systems have moderately higher LCOEs at $0.12/kWh and $0.11/kWh, respectively. While these systems minimize fuel costs, their intermittency and reliance on energy storage contribute to higher operational expenses. Despite its reliability, the Solar-Biomass Hybrid has a fuel cost component that increases its LCOE by $0.10/kWh. Compared to all hybrid configurations, the Diesel Generator Baseline is the least economical, with an LCOE of $0.20/kWh, significantly higher due to its high fuel costs ($0.10/kWh) and frequent maintenance requirements. This finding aligns with previous studies highlighting the cost advantage of renewable hybrid systems over conventional diesel-based power generation. The results demonstrate that hybrid renewable systems, particularly Solar-Wind-Biomass and Solar-Wind-Hydro, provide substantial cost savings while enhancing energy reliability. The configuration choice should consider site-specific resource availability, ensuring an optimal balance between cost efficiency and sustainability.

Environmental Impact

The environmental impact of various hybrid energy configurations was analyzed by assessing annual CO_2 emissions, percentage reduction compared to diesel-based systems, renewable energy contribution, and sustainability ratings. The results highlight the substantial carbon emission savings achieved through hybrid renewable systems. The Solar-Wind-Biomass Hybrid configuration emerges as the most environmentally friendly option, with CO_2 emissions of only 90 tons/year, representing a 77.5% reduction compared to conventional diesel generators. This system also has the highest renewable energy contribution (90%) and a perfect sustainability rating of 5, making it the most sustainable alternative. The Solar-Wind-Hydro Hybrid also demonstrates substantial environmental benefits, reducing CO_2 emissions by 75% while maintaining high renewable energy integration (88%) and a sustainability rating of 4.8. Similarly, the Solar-Biomass Hybrid and Wind-Biomass Hybrid configurations offer emission reductions of 70% and 67.5%, respectively, making them viable sustainable options.

Table 3. Environmental Impact - CO2 Reduction And Sustainability

Hybrid Configuration	Annual CO2 Emission (tons/year)	CO2 Reduction Compared to Diesel (%)	Renewable Energy Contribution (%)	Sustainability Rating (1-5)
Solar-Wind Hybrid	150	62.5	85	4
Solar-Biomass Hybrid	120	70	80	4.5
Wind-Biomass Hybrid	130	67.5	82	4.2
Solar-Wind-Biomass Hybrid	90	77.5	90	5

Hybrid Configuration	Annual CO2 Emission (tons/year)	CO2 Reduction Compared to Diesel (%)	Renewable Energy Contribution (%)	Sustainability Rating (1-5)
Solar-Wind-Hydro Hybrid	100	75	88	4.8
Diesel Generator (Baseline)	400	0	0	1

In contrast, while still significantly cleaner than fossil fuel-based systems, the Solar-Wind Hybrid has a 62.5% CO_2 reduction, attributed to occasional reliance on backup power. However, it maintains a high renewable contribution (85%) and a sustainability rating of 4. As expected, the Diesel Generator Baseline emits the highest CO_2 levels at 400 tons/year, contributing significantly to environmental pollution with no renewable energy contribution and a low sustainability rating of 1. These findings align with previous studies that highlight the effectiveness of hybrid renewable energy systems in reducing carbon footprints. The selection of an optimal configuration should prioritize maximum CO_2 reduction, high renewable integration, and long-term sustainability to align with global clean energy goals.

Challenges and Recommendations

Implementing hybrid renewable energy systems faces several technical hurdles, primarily related to energy intermittency, storage limitations, and grid stability. Solar and wind power variability requires integrating advanced energy storage solutions and smart grid technologies to maintain a stable power supply. Battery costs and efficiency remain key concerns, necessitating investment in improved battery technology and alternative storage methods such as pumped hydro or hydrogen storage. Additionally, ensuring grid stability when integrating renewable energy sources requires advanced grid management and demand response strategies to prevent fluctuations and outages. High initial capital investment and the lack of financial incentives often hinder the widespread adoption of hybrid systems. Many rural or developing regions struggle with limited access to government subsidies and funding, making it difficult to finance renewable energy projects. Phased investment approaches can be introduced to overcome these barriers, allowing for gradual system expansion as funding becomes available. Additionally, strengthening policy frameworks to promote renewable energy incentives, feed-in tariffs, and long-term power purchase agreements (PPAs) can enhance financial viability and investor confidence.

Table 4. Challenges And Recommendations

Category	Challenges	Recommendations
Technical Challenges	Intermittency of renewable energy sources	Integrate hybrid systems with energy storage and smart grid solutions
Technical Challenges	Energy storage limitations and costs	Enhance battery technology and explore alternative storage methods
Technical Challenges	Grid integration and stability issues	Implement advanced grid management and demand response strategies
Policy and Financial Considerations	High initial capital investment	Develop financial models with phased investment approaches
Policy and Financial Considerations	Limited access to government incentives and subsidies	Enhance policy frameworks and promote renewable energy incentives
Policy and Financial Considerations	Uncertainty in long-term financial returns	Ensure economic feasibility through long-term power purchase agreements
Strategies for Scalability and Sustainability	Development of modular and flexible hybrid systems	Encourage adaptive system designs that allow for gradual expansion
Strategies for Scalability and Sustainability	Strengthening local capacity and technical expertise	Provide training programs for local technicians and energy managers
Strategies for Scalability and Sustainability	Encouraging public-private partnerships for investment	Foster collaboration between governments, private sector, and communities

Ensuring long-term sustainability requires a combination of modular system designs, capacity building, and public-private partnerships. Hybrid systems should be developed with scalability, allowing for incremental expansion as demand grows. Strengthening local technical expertise through training programs ensures communities can operate and maintain the systems effectively. Furthermore, fostering collaboration between governments, private sector investors, and local communities can provide sustainable financing mechanisms and improve overall project success. By addressing these challenges through technological innovation, supportive policies, and strategic partnerships, hybrid renewable energy systems can be more effectively deployed and sustained over the long term.

4. Conclusion

This study evaluated the design, optimization, and feasibility of various hybrid renewable energy systems using HOMER Pro, focusing on economic, technical, and environmental aspects. The results highlight that hybrid energy configurations significantly reduce reliance on fossil fuels while improving system reliability and sustainability. The Solar-Wind-Biomass Hybrid system emerged as the optimal configuration, with an installed capacity of 150 kW, an annual energy production of 450 MWh, and a reliability index of 95%. It also had the lowest Levelized Cost of Energy ($0.09/kWh) and the highest carbon emission reduction (77.5%) compared to conventional diesel generators. Similarly, the Solar-Wind-Hydro Hybrid system demonstrated strong feasibility with a 75% CO_2 reduction and an LCOE of $0.095/kWh. Economic viability analysis revealed that renewable hybrid systems reduce energy costs by up to 55% compared to diesel generators with an LCOE of $0.20/kWh. Integrating energy storage and grid management strategies further enhances system cost efficiency and reliability.
In terms of environmental impact, all hybrid configurations significantly reduced carbon emissions. The Solar-Wind-Biomass Hybrid significantly reduced CO_2 emissions to 90 tons/year from 400 tons/year for diesel-based systems. Additionally, sustainability ratings for hybrid systems ranged from 4.0 to 5.0, whereas diesel generation scored 1.0, indicating poor long-term viability. Despite these benefits, several challenges remain, including technical issues related to energy intermittency, high capital costs, and policy constraints. Recommendations include advancing energy storage technologies, implementing phased financial models, and promoting government incentives to encourage investment. Public-private partnerships and local capacity-building initiatives are also crucial to ensuring the long-term success of hybrid renewable systems. This study confirms that hybrid renewable energy systems offer a cost-effective, reliable, and environmentally sustainable alternative to conventional diesel generation. Future research should focus on improving energy storage integration and exploring site-specific optimization strategies to enhance scalability and adoption in diverse rural and urban settings.

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