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Article

A feasibility study and cost-benefit analysis of an off-grid hybrid system for a remote area electrification

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ABSTRACT

Off-grid power production utilizing renewable sources of power has become more significant and viable to meet the limited demands of remote locations. The primary goal of this study is to develop an economic and optimal hybrid PV/Biogas configuration for power production for rural common facilities, including one Primary school, Junior school, and Panchayat Ghar buildings of Sarai Jairam village in Uttar Pradesh, India. Data on the electric load was gathered for two schools and Panchayat Ghar. The PV/biogas hybrid configuration was designed utilizing the Hybrid Optimization Model for Electric Renewable (HOMER), and techno-economic analysis is carried out to fulfill the load requirements. The available biomass potential and the data on solar irradiance of the study area were utilized in the HOMER software to carry out the analysis. The HOMER analysis produced a solution that included total net present cost (NPC) and cost of electricity (COE), and these results were then further improved using sensitivity analysis. The sensitivity analysis employed sensitivity parameters like biomass potential, biomass pricing, solar irradiance, and variation in loads. Based on the NPC and COE, this analysis evaluates the system performance and demonstrates that it is techno-economically feasible.

1. Introduction

The unavailability or shortage of electrical networks in remote locations, the excessive cost of grid extension, and the harsh topography frequently lead to exploring other alternatives. One of the most promising approaches to meet these areas' need for electrification now involves standalone hybrid systems [1]. The grid-connected electricity for power delivery does not always benefit people. For instance, individuals who live in isolated villages, distant farms, and rural locations must rely on autonomous power supply systems that are based on the burning of fossil fuels [2]. The issue is that these systems increase greenhouse gas (GHG) emissions, which in turn lead to air pollution [3]. By utilizing renewable energy sources like solar, wind, biofuels, and others, GHG emissions may be decreased. Rural electrification is crucial to improving the economic and social conditions of rural residents and, eventually, to the development of the country [4-5]. The bulk of the population in India lives in isolated rural regions where they do not have access to grid energy, and expanding the grid is not practical. Furthermore, those remote locations with grid connections only receive a restricted supply once every six to nine hours [6]. In addition, using a diesel generator to get an electric supply is not a practical alternative due to the expense of fuel, maintenance, and operation, as well as the emission of greenhouse gases, etc [7-8]. Additionally, the Government of India is working to promote renewable energy sources by offering various programs, incentives, etc. The Indian government has also set a target of increasing the amount of electricity produced by RES to 450 GW by 2022 [9]. Due to the stochastic nature of RES, a hybrid system that combines two or more sources is a more advantageous and sustainable alternative [10]. Utilizing a variety of simulation and optimization tools and approaches, a great deal of work has been done in this regard. Flavio Odoi- Yorke et al. examined the possibility of using a hybrid solar PV/biogas/battery energy system to provide power to distant areas in Ghana. The objective is to employ locally accessible renewable energy sources to reduce greenhouse gas emissions while achieving a Levelized Cost of Electricity (LCOE). The results show that in terms of cost and pollution savings, PV/biogas/battery systems outperform PV/diesel/battery and diesel-only systems [11]. Endeshaw Solomon Bayu et al. conducted a study to incorporate wind turbines, micro-hydro systems, solar photovoltaic (PV) systems, and battery systems to check the feasibility of hybrid systems to electrify the remote place [12]. Paul et al. examined the economic viability and feasibility of utilizing a hybrid-electricity system in rural areas. The findings show that, when compared to PV/Diesel Generator (DG)/B and isolated DG systems, the photovoltaic (PV)/battery (B) system based on renewable energy (RE) has the lowest net profit cost (NPC) and cost of energy (COE). Although the COE and NPC values of the diesel generator (DG) hybrid-electric system (HES) are lower than those of the PV/DG/B system, the DG system still emits the most substantial pollution [13]. Similarly, Nyagong Santino et al. evaluated the viability of a hybrid power system for a remote South Sudanese community without electricity access. Based on the community's energy requirements, average energy consumption profiles were created over the course of a year. The system was configured and optimized using the HOMER pro application, and based on the standalone mode of operation, six potential combinations were modeled and examined technically and economically. Due to the significant solar potential, the Battery/DG/PV system has the minimum Net Present Cost (NPC) and Cost of Energy (COE) and provides a 22.94% investment return [14].

For the Atacama Desert in Chile, Francisco et al. conducted a cost-benefit analysis of the TEG-HPV system under actual environmental and market circumstances. The economic, electrical, and thermal models of the TEG-HPV system are constructed and examined in MATLAB. With regard to system costs, energy losses, ordinal efficiencies of TEG and PV modules, and their contributions to the economical viability of TEG-HPV systems, five distinct cases are taken into consideration. Payback durations for every scenario are calculated at maximum and minimum PV temperatures for the Atacama Desert, taking into account the industrial and residential prices of electricity [15]. Laetitia et al. conducted a feasibility study with the goal of incorporating renewable energy sources into Popova Island's energy system. It takes an analytical strategy that entails using an energy systems model and the Monte Carlo method before assessing the financial results [16]. Ahmad et al. investigated the feasibility of meeting the load demand with the best system that produces the least amount of CO_2 and net present cost (NPC) emissions. The modeling results demonstrate that the NPC of the proposed grid/PV system is more sufficient than other configurations at the present grid tariff, resulting in a renewable proportion of more than over 50%, a payback period of 17 years, and a 54.3% decrease in CO_2. The outcomes further demonstrate that the integration of a 62 kW PV array with the primary grid is the optimal configuration that results in a minimal COE of 0.0688 $/kWh and sale back power of 9.16% of Al Baha University's total electricity consumption [17]. Mohammad Amin et al. developed the best renewable energy system possible to power a small community using only renewable energy sources. Like many remote Iranian communities, this one experiences regular power shortages. A hybrid stand-alone and on-grid renewable energy system using fuel cells, biogas generators, wind turbines, and photovoltaics is suggested. In addition to the fuel cells, batteries, a hydrogen tank, an electrolyzer or reformer, and other backup and storage components are employed. The major objective is to identify the best design that can fulfill the demand for power while being acceptable from an environmental and an economic standpoint. The findings demonstrate that the cheapest option is to use biogas, wind, and solar rather than adding a fuel cell to this design would raise prices by 33–37% while simultaneously increasing the scalability of the system [18]. It is clearly revealed from the literature that a hybrid energy system with a diesel engine has several benefits over one that is solely powered by a diesel engine, including a longer engine lifespan, lower O&M (Operation and Maintenance) costs, lower fuel consumption and less of an adverse impact on the environment. Such systems still depend on fossil fuel, which is unfriendly to the environment and necessitates logistical arrangements for delivering the fuel to the community, which is the problem with them. Local fuel availability is frequently poor because of expensive transit expenses and theft danger. The diesel engine may be totally replaced with a biogas engine to solve the aforementioned issues, and its fuel can be produced locally in a limited digester. Utilizing locally generated biogas from dung can resolve issues associated with diesel fuel. Furthermore, the literature survey also indicates that HRES is a more reliable and cost-effective source of power than conventional grid systems.

Additionally, the aforesaid research mostly focused on household electrification of rural areas while ignoring the need for power for schools and panchayat ghar. To the author's knowledge, there is no thorough study on the techno-economic analysis of such HRES in using HOMER on the selected location. Also, the creation of such models relied on the use of solar and wind energy, and there are only a small number of studies in which biogas and biomass energy sources were regarded as important sources for generating electricity. İn this regard, an HRE-based power producing system is suggested for supplying continuous electricity to two schools and Panchayat ghar, located in Sarai Jairam village, district Agra, Uttar Pradesh, India. As a consequence, the major goal of this study is to offer the most feasible and most optimized alternative for electrifying panchayat ghar and primary schools situated in distant areas without access to grid electricity. To create the HRES, local RES from the research region is employed. Data on electrical load, solar radiation and biogas were utilized to apply techno-economic analysis utilizing HOMER pro simulations based on sensitivity. The organizational structure of the paper is planned as follows. Section 2 discusses the method of modeling of hybrid systems. Section 3 describes the assessment of electrical load. Section 4 briefly explains the system design and its assessment. Section 5, contains results and discussion and Section 6 presents the conclusions.

2. Method of Modeling Hybrid Systems

For the design and construction of an optimum hybrid system for a rural region, a systematized modeling technique is an integral step since it ensures that the rural population has reliable, consistent and dependable access to electricity

[19]. The HOMER pro software has been utilized as a tool to identify the set of optimum systems that meet the load demand under specific system restrictions and input assumptions [20]. HOMER pro is a distributed power optimization tool designed by the National Renewable Energy Laboratory in the United States [21]. Due to the uncertainties, a sensitivity analysis is conducted to investigate the influence of input assumptions on the optimization outcomes. Figure 1 depicts the process and proposed framework for system modeling and analysis. In the current study, a modeling technique that is shown in the following sections includes a description of the selected location, an assessment of renewable energy sources' potential, electrical load estimation, and system design and optimization procedure.

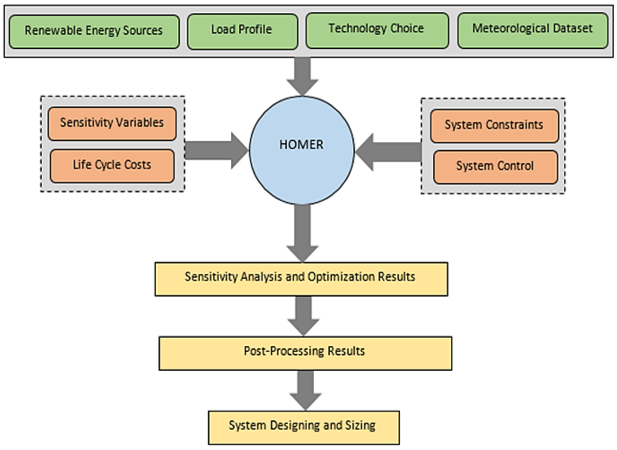

Figure 1. Process and proposed framework for system modeling and analysis

2.1 Location Description

The site for this study was Sarai Jairam village in Uttar Pradesh, India. The abundance of renewable energy and the region's strategic significance was taken into consideration while choosing the location. The location is identified by the coordinates at the longitude of 78o 10.7'E and latitude of 27o 20.2'N and time zone (GMT+05:30) from NASA meteorological data. Figure 2 shows the geographic view of the research location.

Figure 2. The geographic view of the research location

2.2 Assessment of wind and solar resources potential at the selected site

From NASA meteorological data, the solar and wind energy data for Sarai Jairam village have been extracted, and the data are shown in Table 1 with their latitude and longitude (27o 20.2'N, 78o 10.7'E), and time stamp (GMT+05:30). Figure 3 and Figure 4 provide graphical representations of the specifics of solar radiation throughout the course of the year and wind data over the same period. Table 1 provides data on the selected site's annual average daily radiation (kWh/m²/day), clearness index, and wind speed (m/s).

Table 1. Average monthly daily radiation, clearness index, and wind speed

Month	Solar Energy (SE) (kWh/m²/day)	Clearness Index	Wind Speed (WS) (m/s)
Jan	3.670	0.578	4.230
Feb	4.690	0.623	4.690
March	5.590	0.620	5.020
April	6.080	0.589	5.100
May	6.360	0.574	5.250
June	6.010	0.531	5.180
July	4.960	0.444	4.740
Aug	4.540	0.430	4.410
Sept	4.750	0.503	4.150
Oct	4.730	0.595	3.450
Nov	4.030	0.611	3.360
Dec	3.490	0.585	3.700

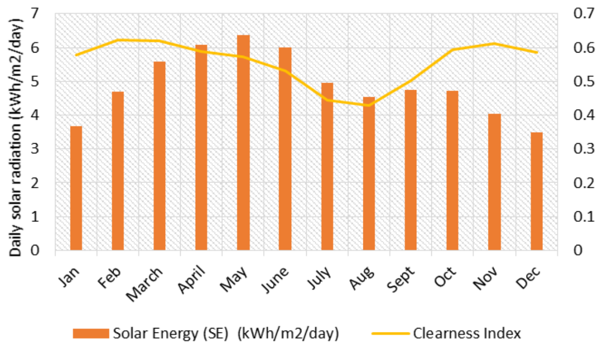

Figure 3. Monthly average solar irradiance throughout the year

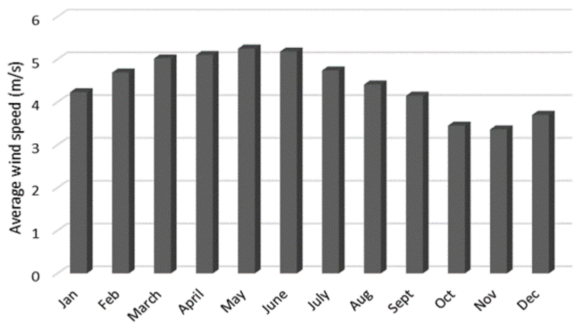

Figure 4. Monthly average wind speed throughout the year

2.3 Assessment of biomass energy resource potential at the selected location

In Sarai Jairam village animal dung may be simply used to produce biogas through the digestion and combustion processes, respectively. Anaerobic digesters are used to treat the manure produced by cattle and produce power. The total dung produced annually from the community is calculated by equation (1);

$$M_n = \sum_{n=1}^{j} N_j m_j \tag{1}$$

Where M_n is the annual total amount of manure produced, N_j is the number of the selected group of animals, n is the overall number of cattle and m_j shows manure produced per cattle [21].

Table 2 lists the number of animals and the availability of animal manure in the village of Sarai Jairam. The total amount of manure produced by all the animals is estimated to be 6.425 tons/day, which may be used to produce 166667.76 kWh of power annually. The total potential of biomass is shown in Figure 5.

Table 2. Total amount of manure produced by all animals

Description	Number of animals	Dung (kg/day/cattle)	Dung availability (kg/day)
Buffaloes	310	15	4650
Cow	175	10	1750
Goat	25	1	25

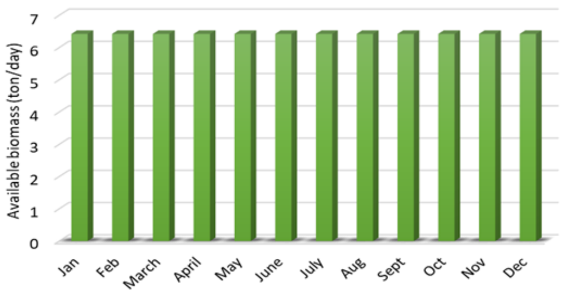

Figure 5. Technical potential of biomass (animal manure)

3. Assessment of Electrical Load

In this work, a hybrid system that employs energy from solar and biogas has been designed to meet the electrical demands of one Primary school, Junior school and Panchayat ghar. The panchayat ghar has two rooms with two fans and four tube lights. The primary school contains six rooms with twelve fans, twelve tube lights, two computers, and one submersible pump, while, five rooms, ten fans, ten tube lights, two computers, and one submersible pump make up the junior high school. Table 3 provides the quantity, power ratings, and power consumption for each load. Figure 6 depicts the electricity load of the proposed region taking into account future expansion. The data has been gathered from the school and panchayat ghar employees.

4. System Design and Assessment

The system configuration shown in Figure 7 includes a PV panel, biogas engine generator, and battery storage with a bidirectional converter. An electric load and biogas generator are connected to the AC bus. The battery storage and PV module are connected to the DC bus. Additionally, the converter is coupled with the AC and DC buses. Table 4 shows the technical specifications and capital costs of components.

Table 3. Electricity load calculation for the selected communities

S.no.		1	2	3	4
Load		Fan	Tube light	Computer	Water pump
Power rating (watts)		60	30	100	500
Panchayat ghar	No. in use	2	4	0	0
	Utilization hours	10	10	0	0
Primary school	No. in use	12	12	2	1
	Utilization hours	8	8	8	1
Junior school	No. in use	10	10	2	1
	Utilization hours	8	8	8	1
Total energy Consumed (Watt)		11760	6480	3200	1000
Total load		22.440kWh			

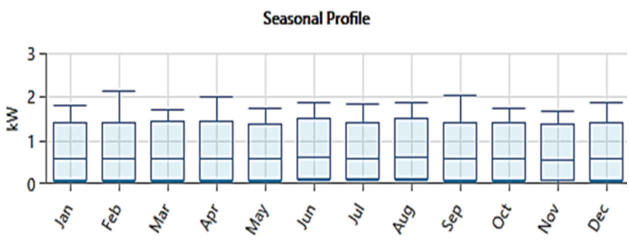

Figure 6. Monthly load profile during the whole year

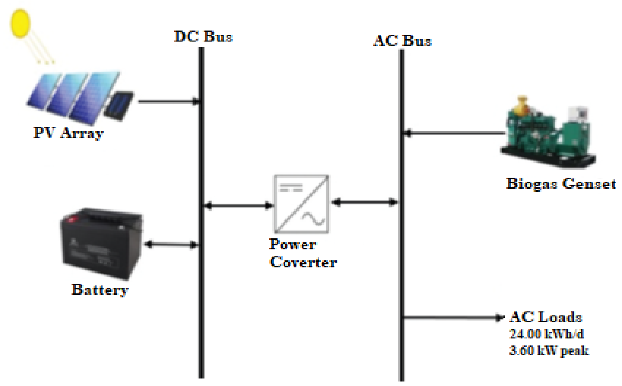

Figure 7. Configuration of off-grid hybrid PV-biogas system

5. Results and Discussion

5.1 System sensitivity analysis outcomes

For technical and economical assessment purposes, the system must be designed with certain constraints or control variables that have an impact on the operating costs and output of the HRES system. Because the developed system is sustainable and the possibilities like the changes in solar radiations and biomass supply were taken into account for the sensitivity analysis. Since animal dung is a free source of biomass, hence, the biomass price was not considered in the system design. It enables planners and designers to select a very efficient and cost-effective method for the specified design parameters. To find out how variations in solar radiation and biomass supply might affect the system economy, both variables were varied. As the supplied biomass was 6.43 tonnes per day, it varied between 6.43-6.50 tonnes per day for the sensitivity analysis, and the solar radiation varied between 4.91-4.99 kWh/m^2/day.

Table 4. Technical specifications and cost of components

Hybrid system components	Specifications	Value
Solar PV	Capital cost	650$/kW
	O&M cost	1$/kW
	Replacement cost	0$/kW
	Sizes	0,1,1.5,2,2.5,3,3.5,4,4.5,5,6,7, 7.5,8,9,10
	Tracking system	No
	Ground reflectance	20%
	Derating factor	80%
	Life span	25 years
	Azimuth,Slope	0
Converter	Capital cost	190$/kW
	Replacement cost	190$/kW
	Sizes	0,1,1.5,2,2.5,3,3.5,4,4.5,5
	Rectifier efficiency	85%
	Capacity relative to inverter	100%
	Inverter efficiency	95%
	Life span	20 years
	Annual rate of interest	0%
Battery	Capital cost	150$/kW
	Replacement cost	30$/kW
	Nominal capacity	1kWh
	Float life	5 years
	Round trip efficiency	80%
	Mninmum state of charge	40%
	Lifetime throughput	917kWh
Biogas generator	Capital cost	250$/kW
	O&M cost	0.08$/kW
	Sizes	0, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5
	Replacement cost	150$/kW
	Biomass cost	$3.75/tone
	Lowest load ratio	30%
	Life span	20000 hours

The sensitivity analysis outcomes of the HRE system are displayed in Table 5, which highlights how changes in the supply of biomass and solar radiation affect the NPC, COE, and operating costs. The findings reveal that as biomass is increased and solar radiation changes are taken into account, net present and operating costs also rise.

5.2 System optimization outcomes

The developed hybrid Photovoltaic/biogas system with sensitivity inputs was modeled in HOMER Pro software by ranging the potential of the biogas generator and solar radiance in order to determine the most efficient, optimized, and cost-effective system for the Primary school, Junior school, and Panchayat ghar in rural areas. To maximize the system's ability to meet the electricity demand, the capacity range of the biomass generator varied between 1kW to 5 kW, while the capacity range of the PV system varied between 4kW to 6 kW. In this study, a 1.50 kW biogas generator, a 5 kW PV array, a 3.25 kW converter, and 30 storage batteries were the optimal and most economically viable configurations evaluated for the hybrid system. This configuration is depicted in Figure 9.

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Table 7 also depicts the share of power production of each component throughout a year, total electricity production, renewable percentage, and excess electricity with unmet load for all different system designs. Figure 8 depicts the average monthly electricity production from a hybrid PV-Biogas system, where orange bars show the power supplied by the photovoltaic panel and green bars show the power generated by a biogas generator. The total initial cost is calculated at $8,743 as shown in Table 6. This is the first investment needed to start the project. The initial cost of Lead acid battery and photovoltaic panels are more as compared to other components as shown in Figure 9. This higher cost is a result of the substantial battery storage capacity, which is intended to offer reliable electricity dispatch when the electricity produced by the power systems is not enough to fulfill the load.

Table 5 Sensitivity outcomes for the hybrid PV/biogas system

Sensitivity		Architecture				Cost			
Solar Scaled Average (kWh/mÂ²/day)	Biomass Scaled Average (t/d)	PV (kW)	Bio (kW)	1kWh LA	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
4.91	6.43	5	1.5	30	3.25	57283	0.614	4547	8743
4.92	6.44	5	1.5	32	3.25	56901	0.610	4483	9043
4.95	6.46	5	1.5	32	3.25	55964	0.600	4396	9043
4.97	6.48	5	1.5	32	3.26	55345	0.594	4337	9044
4.99	6.5	5	1.5	32	3.25	54762	0.587	4283	9043

Table 6 Various different optimized system configurations with economic parameters.

Various Configuration	**NPC ($)**	**COE ($)**	**Operating Cost ($)**	**Initial Cost ($)**
PV/Biogas/Battery/Converter	57283	0.6145	4547	8743
PV/Biogas/Converter	169188	1.8107	15458	4178
Biogas/Battery/Converter	213798	2.3475	19884	1539
Biogas	260688	2.8009	24362	625

Table 7 Electricity generation of different feasible system designs

Parameters	**PV/Biogas/Battery/Converter**	**PV/Biogas/Converter**	**Biogas/Battery/Converter**	**Biogas**
PV array (kWh/year)	7,868 (81.1%)	7,868 (56.2%)	-	-
Biogas generator (kWh/year)	1,830 (18.9%)	6,128 (43.8%)	9,013 (100%)	10,185 (100%)
Total electricity generation (kWh/year)	9,698 (100%)	13,996 (100%)	9,013 (100%)	10,185 (100%)
Renewable fraction (%)	100	100	100	0
Capacity shortage (kWh/year)	0.212 (0%)	143 (1.63%)	2.11 (0.1%)	111 (1.27%)
Excess electricity (kWh/year)	65.0 (0.67%)	5,055 (36.1%)	0	1,466 (14.4%)
Unmet electric load (kWh/year)	0.0000267 (0%)	6.77 (0.0773%)	1.10 (0%)	41.0 (0.468%)

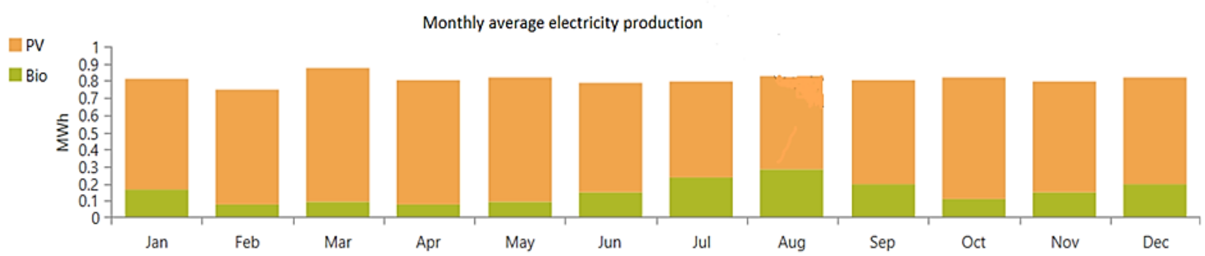

Figure 8. Monthly average electricity generation from the hybrid system

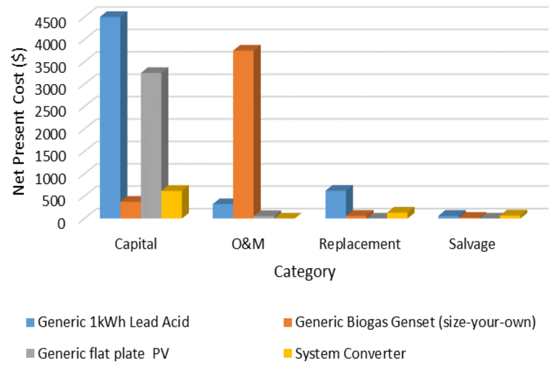

Figure 9. Cost summary of the hybrid PV/Biogas system

In addition, the photovoltaic panels, which are less expensive once installed than a biogas generator, as biomass is available for free, which is why the fuel category has not been presented. Figure 10 displays the power generated by each component, and the total electrical load served is represented in the above plot, while the lower plot shows the unmet electrical load, total renewable power output, ac primary load served, input power, and state of charge of battery over the course of July 9 to July 18 to help with a better understanding of how the system operates.

Table 8 and Figure 8 make it clear that the photovoltaic system consistently outperforms biogas in terms of electricity production. Being off the grid, the system uses solar and biogas as resources to meet the load demands because our maximum demand hours are during the daytime for community load (schools and panchayat ghar) purposes. The capacity factor of the PV modules is about 81.1%, and it operates throughout the year depending on load requirements, producing about 7,868 kWh/year, compared to 1,830 kWh/year from the biomass generator having a capacity factor of 18.9%. Due to the lack of biomass availability throughout the day, biogas power generation is reduced. Furthermore, the system is producing more power than it needs to satisfy its annual power usage of 8,733 kWh, which can be saved or used for other productive purposes.

6. Conclusion

This study offers a technical and economical assessment of different stand-alone solutions for Primary school, Junior school, and Panchayat Ghar buildings of Sarai Jairam village in Uttar Pradesh, India. HOMER pro analyzed several hybrid PV-biogas system configurations by modeling a dynamic hybrid model. An ideal solution was suggested based on the cost analysis after these hybrid designs underwent sensitivity analysis using variables such as solar radiation, biomass resource, and system sizing. In this study, the combination of a 1.50 kW biogas generator, 5 kW PV array, a 3.25 kW converter, and 30 storage batteries was found to be the most cost-effective option with a total capital cost of $8,743, Net Present Cost (NPC) of $57,283 and Cost of Energy (COE) $0.61, respectively. This hybrid renewable energy system produces roughly 9,698 kWh per year, with an additional 965 kWh per year being generated to make the study area grid-independent. Additionally, the system has an estimated payback period of 0.41 years and a favorable net current cost for a projection timeframe of 25 years. By providing rural areas with these hybrid renewable energy systems, the Indian government may significantly contribute to resolving the country's current energy crisis. Additionally, the existing legislation that supports the use of such systems only offers tax breaks or reductions, which is insufficient to allow low-income populations to make use of these systems. The government may alter its supporting policies, offer rewards for system employment, and launch a national electrification campaign. Similar studies could be undertaken for other rural places in order to electrify them, which would also help the Indian government achieve its goal of "Power to all."

Table 8. Annual generation and consumption of electricity by a hybrid system

Generation	kWh/year	%	Consumption	kWh/year	%
PV Modules	7,868	81.1	AC primary load	8,733	100
Biogas Generator	1,830	18.9	DC primary load	0	0
Total	9,698	100	Total	8,733	100

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

Author contributions

Mohammad Rizwan: Conceptualization and supervised the research; Upma Singh: Methodology; resources; validation; formal analysis; writing the original draft. Both authors contributed to the analysis of the findings, critically reviewed and edited the manuscript, and approved the final version for submission.

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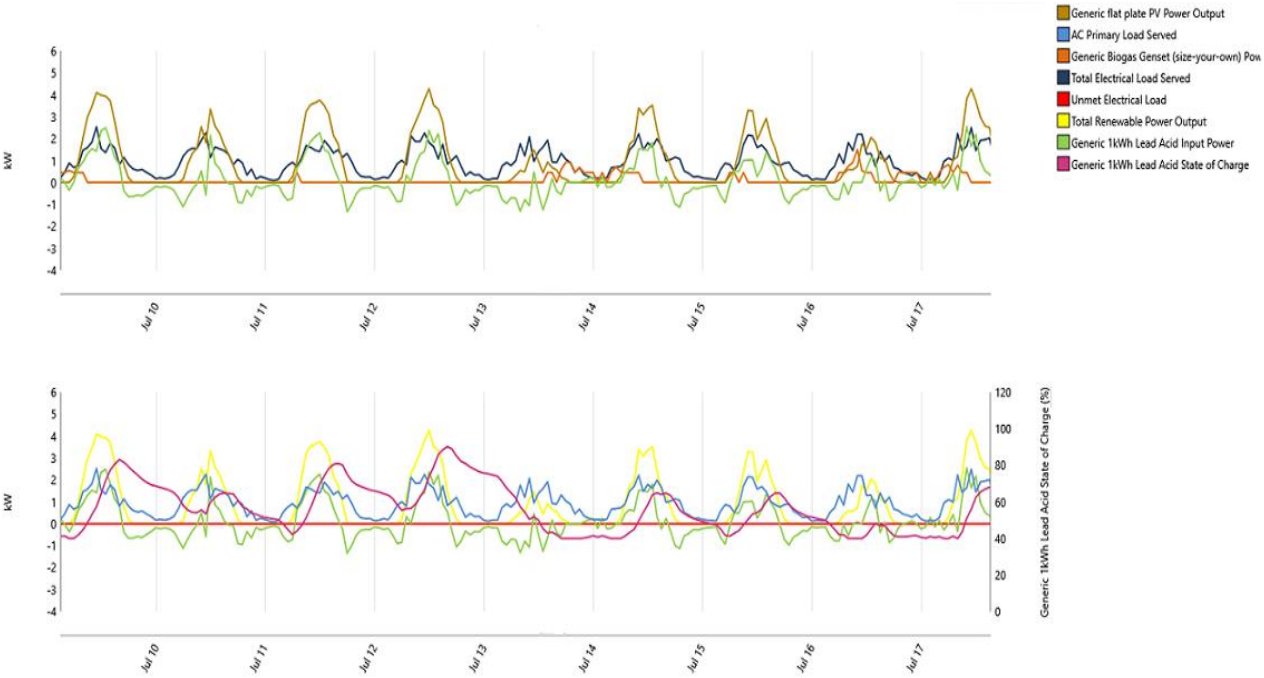

Figure 10. Total electrical load served, unmet electrical load, total renewable power output, state of charge of the battery, ac primary load served and generated power by each component during July 9 to July 18.

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