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Techno-Economic Analysis of a PV-Biogas Hybrid Renewable Energy System for Rural Electrification

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Abstract: The increasing demand of clean and reliable electricity in the rural setting has also contributed to the increased development of hybrid renewable energy systems with these systems having various forms of renewable energy. This paper examines both the cost-effectiveness and technical efficiency of a system which uses solar and biogas to generate electricity and deliver it to rural communities. The system will consist of solar panels, biogas generator, energy-storing batteries, and converter to regulate the electricity supply. The weather databases were used to provide the data on the sunshine and temperature, and the electricity demand was calculated depending on the average requirements at the rural territory. Using the HOMER Pro software, the system configuration has been configured and tuned to identify the most cost-efficient system configuration depending on the total cost per time frame and average energy cost. The optimal design will consist of 10 kilowatts of solar panels, 500 kilowatt biogas generator, 30 lead-acid batteries and 10 kilowatt converter. The findings indicate that its overall cost per kilowatt-hour is a total of 6,435 and the average cost of energy is 0.121. The sensitivity analysis was carried out to understand the certain ways in which the amount of sunlight on the surface and the amount of the use made on the generator influence the performance of the system. The results indicate that this hybrid system is dependable and has lower operation costs and less environmental damage. The solar and biogas hybrid system is then a good option to supply clean and secure energy in the rural settings.
Keywords: Hybrid renewable energy system, photovoltaic, biogas generator, Wind Turbine, HOMER Pro, techno-economic analysis, rural electrification.

I. INTRODUCTION

The consumption of energy is increasing at a high rate globally due to an increase in population and the rise in industries. Fossils used in power systems are associated with great deal of pollution and emission of toxic gases to the atmosphere. Due to that, there is an increased desire to switch to cleaner sources of electricity generation, such as solar, wind, and biomass.

This is because solar power is popular as it is readily available and has fewer effects on the environment. However, solar energy is not always there as a matter of fact depending on the weather. Hybrid systems that use solar in combination with other sources of energy such as biogas or biomass have also been used to enhance reliability of energy. Biogas systems transformation involves the use of the organic wastes to produce electricity that can be generated continuously and regulated. Solar powered biogas will enable the energy system to be more reliable and not dependent on fossil fuels.

These hybrid energy systems are designed and optimized with special tools such as HOMER Pro. The tools are useful in identifying the optimal configuration depending on the amount of energy required, the amount of resources at the disposal of an organization, and the cost of that specific setup.

This paper examines the design and enhancement of a system that combines the use of solar panels and biogas to run remote locations. It is aimed at locating the most cost-efficient arrangement and testing its effectiveness with the help of HOMER Pro.

II. LITERATURE REVIEW

The partnership between renewable energy sources and traditional energy remedies has become a viable and sustainable environment response to the world's growing electricity demand, the use of finite fossil fuels, and to environmental issues, like the emission of greenhouse gases. The high population growth, urbanization and industrialization have exposed the world to the high consumption of energy. The traditional source of energy cannot be used to address this increasing demand because it is not in abundance and there are its effects on the environment. Solar and wind energy sources are also renewable and non-polluting to the environment but their intermittency and stochastic characteristic makes them incapable of offering constant energy resources. Thus hybrid systems which combine various renewable sources as well as conventional backup systems have been shown to be necessary to a reliable and stable generation of energy [1]-[3].

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Some studies have also outlined the significance of decentralized hybrid renewable energy systems to rural electrification, particularly in remote and isolated areas where the extensions of the grid system are not technically feasible and costly. It has been pointed out that a decentralized hybrid system is the most economical option when the distance between the leading grid is past a certain economic threshold which is the breakeven economic distance [4]-[6]. These systems do not only guarantee a stable supply of power but also aid socio-economic development by enhancing the living standards, sustaining the local industries, and providing employment opportunities. In addition, decentralized systems minimize transmission losses and improve energy accessibility to underserved regions.

The literature has examined a broad list of formulations of hybrid systems that consist of photovoltaic (PV), wind turbines, biomass generators, biogas systems, diesel generators, and energy storage devices. Research shows that a combination of more renewable sources will enhance the reliability and minimise reliance on fossil power. Specifically, biomass-based hybrid systems have also come into focus because of its capacity to offer sustained and dispatchable power. The use of biomass resources that are locally grown (rice husk, crop residues, and pine needles) helps not only the generation of energy but also in solving what concerns waste disposal and open burning problems into the environment [7]-[9]. Also, the fact that diesel generators are also included as backup energy sources increases the reliability of the system when the generation of renewable energy is low.

Energy storage systems are important in the hybrid renewable energy systems because they reduce the unpredictability of renewable sources. Storage devices are mostly used in the form of batteries which allow provision of a back supply of power when there is low generation and also to ensure constant supply of power. Comparative studies involving various configurations like PV/battery, wind/battery and PV/wind/battery systems have indicated that hybrid systems with built-in storage have high techno-economic performance and reliability [10]-[11]. Nevertheless, storage component sizing is very important, and an over-sized system adds more expenses, and an under-sized system compromises the reliability.

The hybrid systems have been widely designed and analysed using simulation and modelling tools. IT programs like HOMER, TRNSYS, SAM and Energy Plus allow researchers to compute the performance of a system under diverse climatic and load conditions. One of them is HOMER which has been popular in the analysis of techno-economic, optimal sizing and sensitivity analysis of hybrid systems. They can measure the performance indicators in terms of cost of energy (COE), net present cost (NPC), payback period, and system reliability [12]-[14]. Sensitivity analysis can be used especially to learn the effects of changes in the parameters like solar radiation, wind speed, fuel prices and load demand on the system performance.

The methods of optimization play a crucial role in finding the most efficient choice of hybrid systems. Classical methods of optimization are computationally inexpensive and easy to use but cannot solve complicated multi-objective problems. Methods based on artificial intelligence, including particle swarm optimization, genetic algorithm, and neural networks, are more accurate and convergent, but have complex programming and extra computing power needs. Combination of the features of classical and artificial methods is seen in hybrid optimization methods which provide better performance of the system and less time of computation but introduce extra complexity in the implementation [15]-[17].

Another issue that is important to the effective performance of hybrid renewable energy systems is the control strategies and energy management systems. Combination of centralized, distributed and hybrid control techniques has been examined and distributed, and hybrid control techniques have proved to be more effective than the centralized technique as they are flexible and they also allow individual management of respective components. These are strategies that enhance reliability of the system, reduce chances of failure and also increase the efficiency of the system. The energy management systems are normally set to pursue techno-economic goals, which include reducing the cost of operation, maximizing use of renewable energy, and power reliability [18]-[19].

There is a lot of literature in form of case studies in various geographical areas such as India, Bangladesh, Spain, Nigeria and Saudi Arabia that show the versatility and efficiency of hybrid systems within various climatic and load conditions. These studies disclose that availability of resources, load demand and economic conditions determine the feasibility of hybrid systems. The grid-connected hybrid systems are usually cheaper because of its lesser reliance on storage and diesel generators whereas standalone system is more applicable in fully isolated places [20]-[22]. Hybrid systems in most instances have proven useful in reducing greenhouse gas emissions over traditional diesel-based systems, which are sustainable to the environment.

One important feature of evaluation of hybrid systems is the economic analysis. System feasibility is usually considered in terms of its parameters, cost of energy (COE), net present cost (NPC), internal rate of return (IRR) and payback period. Research has shown that the parameters depend on configurations of systems, availability of resources as well as the state of the economy. Subsidies, policies and incentives of the government are very instrumental in encouraging the implementation of the hybrid systems, lowering the initial investment and enhancing financial feasibility [23]. Also, the fact that hybrid systems can produce surplus power and place it into the grid only results in the further augmentation of their economic advantages.

The literature shows well the environmental merits of hybrid renewable energy systems. Such systems tremendously decrease the emission of greenhouse gases and reliance on fossil fuels, which are associated with mitigating climate change. The combination of renewable energy sources and the use of biomass also makes a greater contribution to the sustainability of the environment by decreasing the wastefulness and increasing resource efficiency. Besides, hybrid systems contribute to independence of energy sources and decreased dependence on centralized power generation which is one of the necessary conditions of sustainable energy development.

III. METHODOLOGY

A. *System Architecture*

The solar power system converts sunlight into electricity and biogas generator assists in supplying power in times of low sunshine. The batteries accumulate additional electricity and release them when the demand is high or when there is insufficient solar energy being generated.

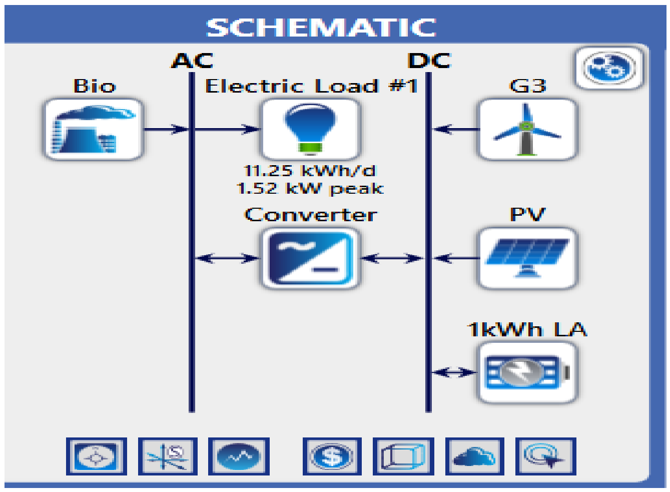

Figure 1: Hybrid PV–Biogas system configuration

Table 1: System Component Specification

Sr. No	Component	Capacity
1	PV Array	10 kw
2	Biogas Generator	500 kw
3	Battery	1 kwh
4	Number Of Batteries	30
5	Converter	10 kw

B. *Modeling the Solar Photovoltaic System*

The solar photovoltaic system transforms the sunlight into electricity. The degree of power it generates is determined by the amount of sunlight, the efficiency of panels and their temperature. This equation was used to calculate the power output of the PV system:

$$P_{PV} = Y_{PV} \times f_{PV} \times \frac{G_T}{G_{STC}}$$

Where:

P_{PV}= Output power of the PV array (kW)

Y_{PV}= Rated capacity of the PV array (kW)

f_{PV}= Derating factor for the PV system

G_T= Amount of sunlight hitting the PV array (kW/m²)

G_{STC}= Standard sunlight level (1 kW/m²)

The source of most energy in the hybrid system is solar energy since it is universally present and reliable.

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Figure 2: Average solar radiation for each month in the study area.

C. *Modelling the Wind Turbine*
Figures Wind energy is converted into electricity through wind turbines. The rate of power they generate is determined by the speed of the wind, the air density in the air, and the turbine design. The wind turbine is powered on by an equation that is calculated as follows:

$$P = \frac{1}{2}\rho A V^3 C_p$$

Where:

P= Power output (W)

ρ= Air density (kg/m³)

A= Area covered by the turbine blades (m²)

V= Wind speed (m/s)

C_p= Power efficiency factor

Wind turbine is complementary to solar PV as there are chances that the wind could blow at night or during clouds.

D. *Modelling the Biomass Generator*
The biomass generator uses organic waste such as farm waste or unused vegetation to generate electricity. The biomass is taken as renewable source of energy since fuel can be naturally replenished.

The biomass generator can power the generator by the amount of fuel consumed and the efficiency of the generator. In hybrid renewable systems biomass generators can act as a backup supply of power to ensure that there is power even when solar and wind power is inadequate.

E. *Battery Energy Storage System*
Authored by renewable sources, the battery storage system stores additional power which is then distributed when the quantity of electricity produced is insufficient. State of Charge (SOC) of the battery is derived through the following equation:

$$SOC - \frac{E_{stored}}{E_{max}}$$

Where:

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SOC = State of charge

E_{stored}= Energy stored in the battery

E_{max}= Maximum battery capacity

Importance of battery storage is to make the system more reliable as well as to match energy supply to what is required.

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F. Load Profile

The electrical load demonstrates the required amount of electricity by the system. This is calculated at an hourly basis in the model to show the amount of energy used in a day. The load profile is another significant aspect of system design since it enables deciding the necessary amount of power to be produced as well as to what size the battery storage should be.

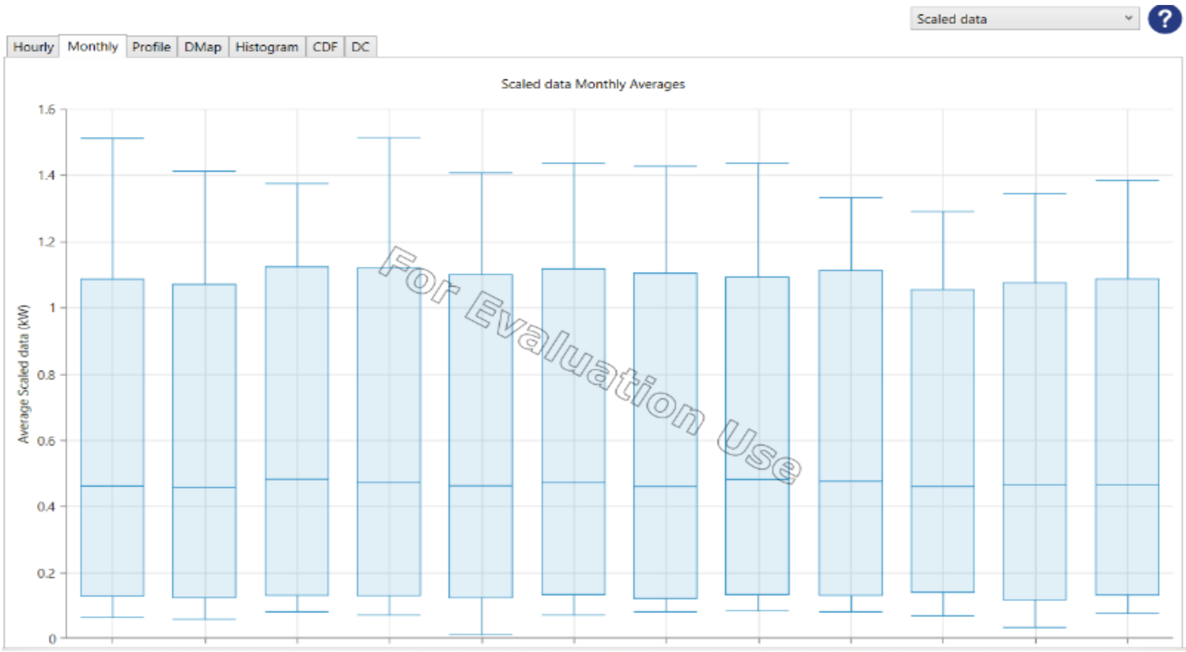

Figure 3: Load duration curve of the electricity demand

The power consumption taken as the basis of the present study represents the type of energy consumption in a small village or a rural home.

Average daily load = 11.25 kWh/day

Peak demand = 1.52 kW

The load profile indicates that the largest amount of electricity is consumed during the evening period on activities such as lighting and operating household facilities. Hourly, monthly and annual changes in electricity use were studied by using HOMER Pro tools.

G. Economic Analysis

The Net Present Cost (NPC) is the total cost of the system over its lifetime.

$$NPC - \frac{C_{ann}}{CRF(i,N)}$$

Where:

C_{ann}= Total annualized cost

i= Interest rate

N= Project lifetime

IV. SIMULATION RESULT

A. *Optimization System Configuration*

The HOMER Pro optimization demonstrates several potential system arrangements. Any arrangement that has the lowest Net Present Cost (NPC) is selected as the solution of choice.

Table 2: Optimization Result

Sr. No	Parameter	Value
1.	Net Present Cost (NPC)	$6,435
2.	Levelized Cost of Energy (LCOE)	$0.121/kWh
3.	Initial Capital Cost	$3,725
4.	Operating Cost	$209.62/year
5.	Capital Cost	$3,725

The most cost-effective solution to the hybrid renewable energy system appears as the first row of the table. These findings demonstrate that the system can deliver electricity at a significantly lower cost when compared to the traditional off-grid power systems.

B. *Annual Energy Production*

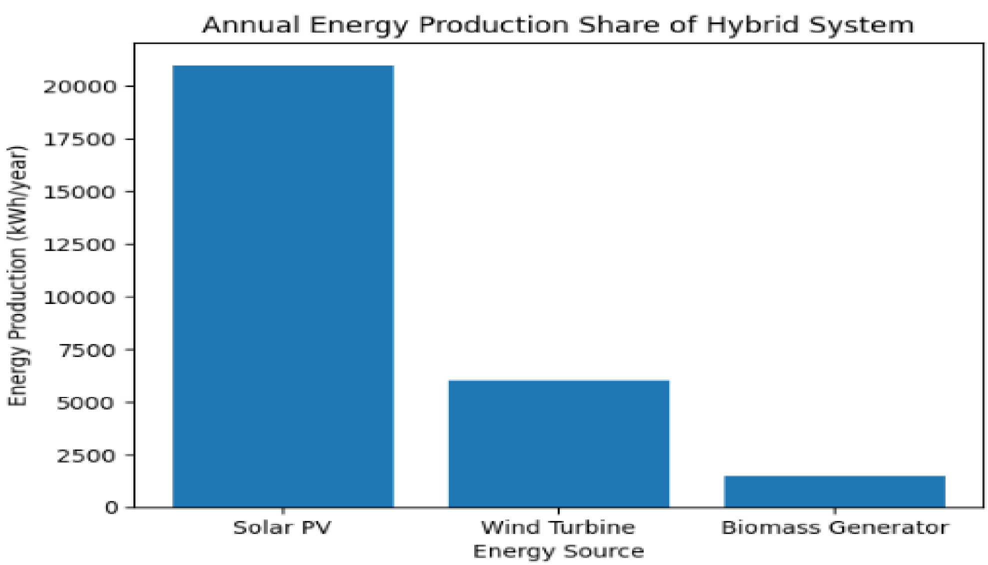

Figure 4: Annual Energy Production Graph

Figure 4.1 shows the quantity of electricity generated annually by the hybrid system. The findings indicate that solar photovoltaic system produces the highest electricity of approximately 21,000 kWh/year. Approximate 6000 kWh/year of electricity is generated by the wind turbine, and an additional 1500 kWh is generated by the biomass generator. This demonstrates that solar power is the primary source of energy, whereas wind and biomass are to support the main generated power and make the system more reliable.

C. *Sensitivity Analysis*

The sensitivity analysis was conducted to determine the influence of various factors on the economic performance of the system. The variables under analysis are:

- Solar radiation levels
- Biogas generator minimum load ratio

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The findings reveal that even with varying solar radiations, the hybrid PV-biogas system remains the most economical. In case the solar radiation reduces, the biogas generator compensates the reduced solar output and maintains a constant supply of electricity.

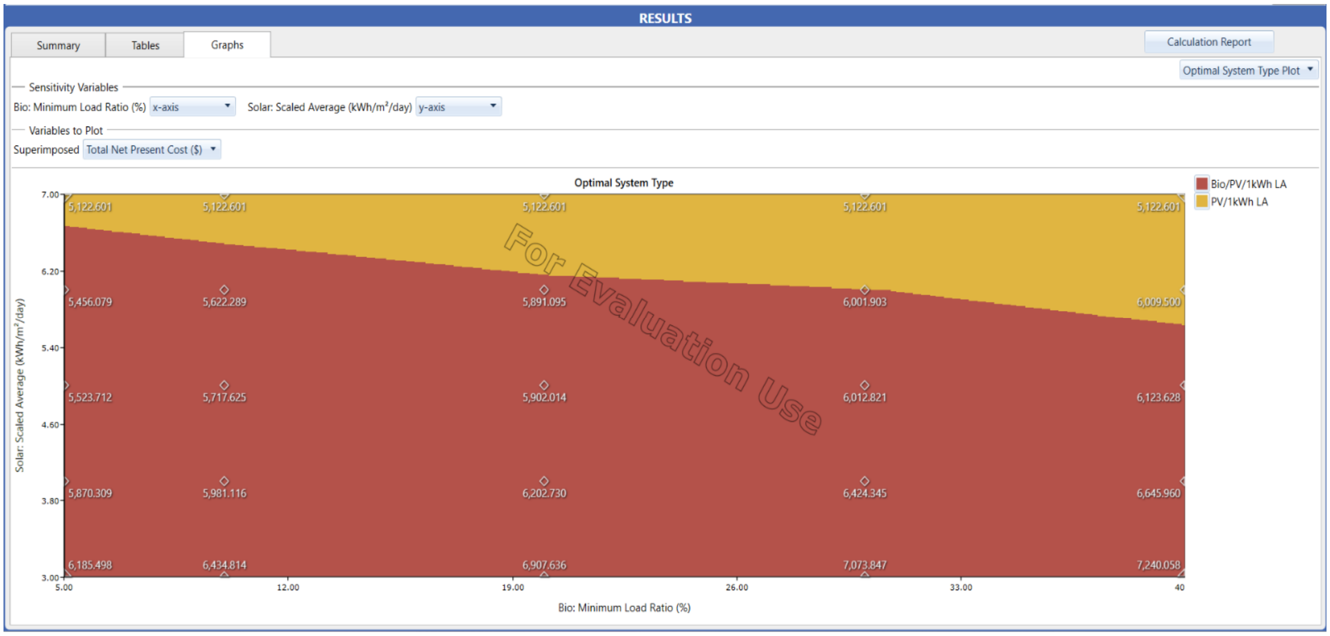

Figure 5: Sensitivity Analysis Showing Impact of Solar Radiation and Biogas Load Ratio

This demonstrates the reliability of the system, and it demonstrates the advantages of using the energy sources that are based on solar and biomass. The initial row in the optimisation results table denotes the least expensive design of the hybrid renewable energy system. The results achieved go to show that the proposed system can offer electricity at a considerably reduced cost than the traditional off-grid power systems.

D. Battery Storage Performance

The daily state-of- charge (SOC) profile is used to study performance of the battery storage system as shown in Figure. The SOC profile indicates the behaviour of charge and discharge for 24 hours involving battery.

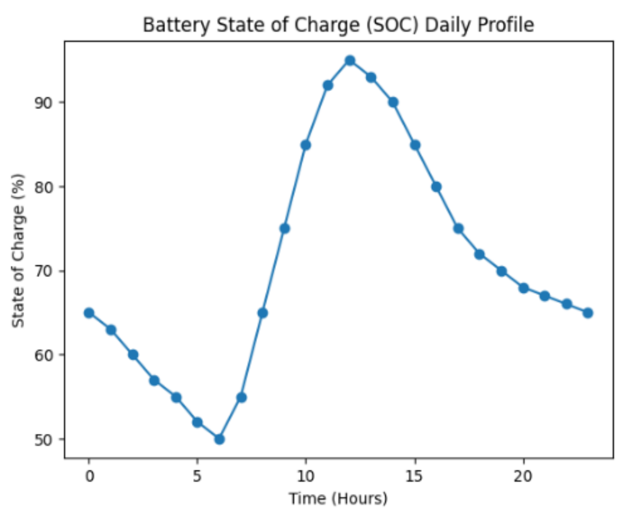

Figure 6: Daily battery state-of-charge profile

During the morning hours, the SOC of the battery decreases very slowly since electricity is in use and there is not much renewable energy, which can be produced.

When the sun comes out on a day the solar PV system begins generating surplus electricity than what is required. This additional electricity is channelled to charge the battery resulting in the SOC rising and it is reaching approximately 95 percent by midday.
The battery discharges accumulated electricity to serve the demand in the evening hours when electricity consumption is increased and there is a reduction in solar energy production. This brings the SOC down once more till the subsequent charging cycle commences. The battery storage provides stabilization to the energy balance of the system and maintains a constant power supply of the hybrid system.

E. Renewable Energy Fraction

Figure 4.4 represents the fraction of renewable energy of the hybrid system. The findings indicate that approximately 92-percent of the total energy demand is supplied by renewable energy sources whereas 8-percent of the sources are non-renewable sources or as a backup system.

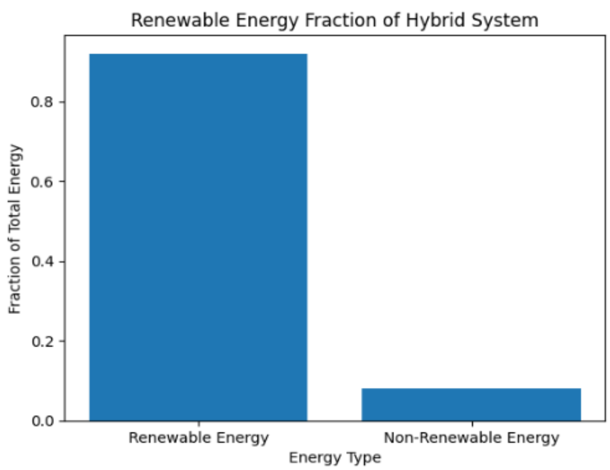

Figure 7: Renewable energy fraction

This great percentage of renewable energy exploitation demonstrates that the system is environmentally friendly. With maximum utilization of solar, wind, and biomass energy, the system reduces the emission of greenhouse gases and does not entirely depend on fossil fuels. Having more renewable energy will also make the system more efficient and will aid in securing a steady supply of energy to the rural and remote regions.

F. Economic Analysis

It was determined that based on cash flow and net present cost (NPW) analysis, the hybrid energy medium derived from renewable sources was economically viable as illustrated on Figure. Cumulative profile is a cost profile that depicts the amount of money used within the 20 years period of using the system.

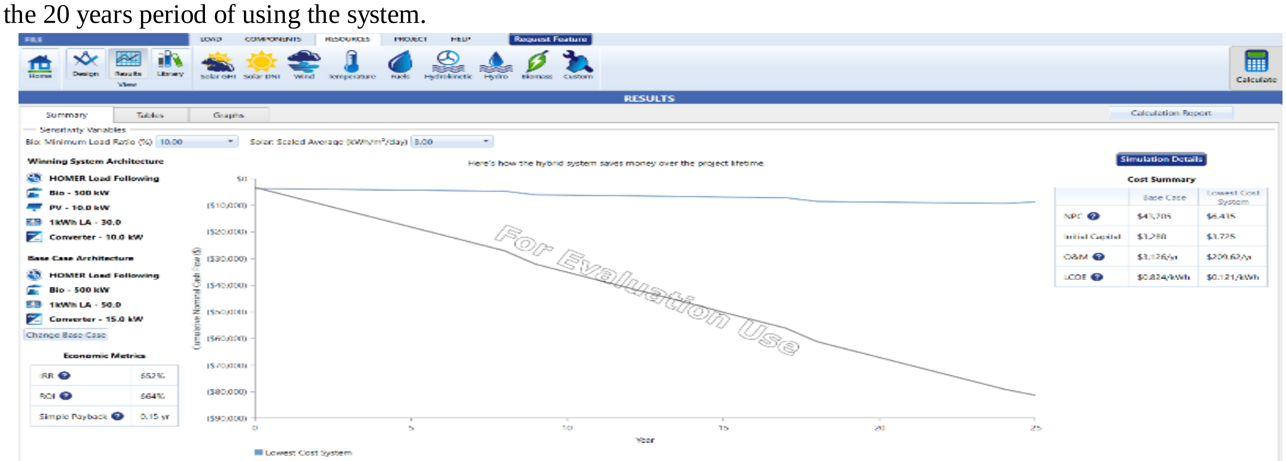

Figure 8: Cumulative cash flow over project lifetime

The initial period takes the greater part of the money, as the cost of installing the solar panels, wind turbines, batteries and other components is costly. But the operating and maintenance cost remains low since it consumes renewable energy. In the long run, the hybrid system is economical as it has constant operation costs.

The findings indicate that the proposed system is an excellent investment and can save money in the long term than the traditional diesel-based power systems.

Table 3: Economic Performance

Sr. No	Parameter	Value
1.	Net Present Cost	$6435
2.	Levelized Cost of Energy	$0.121/kWh
3.	Initial Cost	$3725
4.	Operating Cost	$209/year
5.	IRR	652%
6.	ROI	664%
7.	Payback	0.15 year

V. CONCLUSIONS

This paper has examined a step-by-step cost and technical effort to examine a system incorporating the combination of various renewable energy sources, such as solar panels, a biogas generator, batteries, and a power converter. The HOMER Pro was used to develop and trial the system to identify the optimal structure to supply electricity to remote locations.

The results show that the best setup includes a 10 kW solar panel system, a 500 kW biogas generator, 30 lead-acid batteries, and a 10 kW converter. The total cost of this installation is 6435 during the life of the installation, and the cost of 1kWh of electricity per unit is 0.121 (unit) so it is a good cheap alternative in producing power in remote areas. The solar energy, in combination with biogas will maintain the power supply constant because the biogas will be available to provide the alternative times when the sun is not shining.

The experiment has also ensured the performance of the system in varying weather and usage and concluded that it is good to be used even when quantity of sunlight or power requirements vary. The results indicate that biogas as a source of energy can be used to ensure sustainable electricity and lower the quantity of toxic gases in the atmosphere. The system is greener and less expensive in the long run when compared to the more traditional methods of generating electricity through fossil fuels.

All in all, this analysis reveals that intending to use solar and biogas energy together is a viable solution to providing the reliable electricity to rural communities and especially where there is plenty of sunlight and biomass retention. The further work may focus on adding additional sources of renewable energy such as wind energy and means to store energy to make the system even more efficient and economical.

VI. ACKNOWLEDGMENT

The demand for reliable and clean electricity in rural and remote areas has accelerated the advancement of hybrid renewable energy systems. This study examines the expenses and technology of a system that employs solar panels, wind turbines, and a biomass generator, supplemented by batteries, to provide electricity to rural regions. Using HOMER Pro, the system is designed and improved based on the resources that are available in the area and the area's electricity needs. The setup uses different kinds of energy sources that can be used when needed, making sure that the power supply is always steady.

The simulation results show that the best version of this mixed system costs $6,435 in total and $0.121 per kilowatt-hour of energy, which shows that it is a good value. The study of energy production shows that solar panels make the most electricity, followed by wind and biomass. This means that the system will still work well even if the weather changes. The batteries help keep the system balanced by holding extra energy and letting it go when it's needed.

The system also uses a lot of renewable energy, which cuts down on harmful gas emissions a lot compared to systems that use fossil fuels. A close look at the setup shows that it is still cheap even when the amount of sunlight or other factors change. The results show that a mixed renewable energy system is a good, cheap, and dependable way to get electricity to places that are hard to reach.

REFERENCES

[1] Pavankumar, Y., Kollu, R., & Debnath, S. (2021). Multi-objective optimization of photovoltaic/wind/biomass/battery-based grid-integrated hybrid renewable energy system. IET Renewable Power Generation, 15(7), 1528-1541.

[2] Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. Results in engineering, 20, 101621.

[3] Ayman Abdul Karim Alhijazi, Radwan A. Almasri ,and Ahmad Firas Alloush. A Hybrid Renewable Energy (Solar/Wind/Biomass) and Multi-Use System Principles, Types, and Applications: A Review. Sustainability 2023, 15(24), 16803 [scholar.google.com]

[4] Hossen, M. D., Islam, M. F., Ishraque, M. F., Shezan, S. A., & Arifuzzaman, S. M. (2022). Design and implementation of a hybrid solar-wind-biomass renewable energy system considering meteorological conditions with the power system performances. International journal of photoenergy, 2022(1), 8792732.

[5] Zhang, X., Yang, J., Fan, Y., Zhao, X., Yan, R., Zhao, J., & Myers, S. (2020). Experimental and analytic study of a hybrid solar/biomass rural heating system. Energy, 190, 116392.

[6] Patil, A. A., Arora R., Arora, R., & Sridhara, S. N. (2024). Techno-economic analysis of solar, wind and biomass hybrid renewable energy systems in Bhorha village, India. Journal of Atmospheric and Solar-Terrestrial Physics, 265, 106362.

[7] Patil, A. A., Arora, R., Arora, R., & Sridhara, S. N. (2024). Techno-economic analysis of solar, wind, and biomass hybrid renewable energy systems to meet electricity demand of a small village in Bihar state of India. Nature Environment and Pollution Technology, 23(3), 1261-1283.

[8] Talukder, M. J., Hosen, M. M., & Khan, M. R. (2022). Hybrid renewable energy systems: Integrating solar, wind, and biomass for enhanced sustainability and performance. WIND, AND BIOMASS FOR ENHANCED SUSTAINABILITY AND PERFORMANCE (July 05, 2022).

[9] Channi, H. K., Giri, N. C., Sandhu, R., El-Sebah, M. I. A., & Syam, F. A. (2024). Potential and economic feasibility analysis of solar-biomass-based hybrid system for rural electrification. Bulletin of Electrical Engineering and Informatics, 13(6), 3833-3840.

[10] Ganthia, B. P., Sasmita, S., Rout, K., Pradhan, A., & Nayak, J. (2018). An economic rural electrification study using combined hybrid solar and biomass-biogas system. Materials Today: Proceedings, 5(1), 220-225.

[11] Khare, V., Nema, S., & Baredar, P. (2016). Solar–wind hybrid renewable energy system: A review. Renewable and Sustainable Energy Reviews, 58, 23-33.

[12] Anand, P., Bath, S. K., & Rizwan, M. (2017). Design of solar-biomass-biogas based hybrid system for rural electrification with environmental benefits. International Journal on Recent and Innovation Trends in Computing and Communication, 5(6), 450-456.

[13] Ammari, C., Belatrache, D., Touhami, B., & Makhloufi, S. (2022). Sizing, optimization, control and energy management of hybrid renewable energy system—A review. Energy and Built Environment, 3(4), 399-411.

[14] Figaj, R., Żołądek, M., Homa, M., & Pałac, A. (2022). A Novel Hybrid Polygeneration System Based on Biomass, Wind and Solar Energy for Micro-Scale Isolated Communities. Energies, 15(17), 6331.

[15] Malik, P., Awasthi, M., & Sinha, S. (2020). Study of grid integrated biomass-based hybrid renewable energy systems for Himalayan terrain. International Journal of Sustainable Energy Planning and Management, 28, 71-88.

[16] Kaur, M., Dhundhara, S., Verma, Y. P., & Chauhan, S. (2020). Techno-economic analysis of photovoltaic-biomass-based microgrid system for reliable rural electrification. International Transactions on Electrical Energy Systems, 30(5), e12347.

[17] Rajbongshi, R., Borgohain, D., & Mahapatra, S. (2017). Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER. Energy, 126, 461-474.

[18] Bhattacharjee, S., & Dey, A. (2014). Techno-economic performance evaluation of grid integrated PV-biomass hybrid power generation for rice mill. Sustainable Energy Technologies and Assessments, 7, 6-16.

[19] AlKassem, A., Draou, A., Alamri, A., & Alharbi, H. (2022). Design analysis of an optimal microgrid system for the integration of renewable energy sources at a university campus. Sustainability, 14(7), 4175.

[20] Sahu, P.K., Jena, S. and Sahoo, U. (2021). Techno-Economic Analysis of Hybrid Renewable Energy System with Energy Storage for Rural Electrification. In Hybrid Renewable Energy Systems, U. Sahoo (Ed.). https://doi.org/10.1002/9781119555667.ch3

[21] Abbaspour A, Jahed A, Ahmadi A. Techno-economic analysis of PV–wind–diesel–battery hybrid power systems for industrial towns under different climates in Spain. Energy Sci Eng. 2023;11:2831-2850. doi:10.1002/ese3.1495

[22] Olatomiwa, L., Mekhilef, S., Huda, A.S.N. and Sanusi, K. (2015), Techno-economic analysis of hybrid PV–diesel–battery and PV–wind–diesel–battery power systems for mobile BTS: the way forward for rural development. Energy Sci Eng, 3: 271-285. https://doi.org/10.1002/ese3.71

[23] Obileke, K. and Mukumba, P. (2025), Techno-Economic Evaluation of Wind and Bio-Energy Systems for Sustainable Development: A Systematic Review. Energy Science & Engineering, 13: 2179-2202. https://doi.org/10.1002/ese3.70025

[24] Rumi Rajbongshi, R. R., Devashree Borgohain, D. B., & Sadhan Mahapatra, S. M. (2017). Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER.

[25] Mukhopadhyay, S., Soonee, S. K., Joshi, R., & Rajput, A. K. (2012, July). On the progress of renewable energy integration into smart grids in India. In 2012 IEEE Power and Energy Society General Meeting (pp. 1-6). IEEE.

[26] Cao, B., Dong, W., Lv, Z., Gu, Y., Singh, S., & Kumar, P. (2020). Hybrid microgrid many-objective sizing optimization with fuzzy decision. IEEE Transactions on Fuzzy Systems, 28(11), 2702-2710.

[27] Tazay, A. F., Samy, M. M., & Barakat, S. (2020). A techno-economic feasibility analysis of an autonomous hybrid renewable energy sources for university building at Saudi Arabia. Journal of Electrical Engineering & Technology, 15(6), 2519-2527.