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OPTIMIZATION OF A HYBRID RENEWABLE ENERGY SYSTEM (HRES) WITH GRID INTEGRATION USING HOMER SOFTWARE AND MACHINE LEARNING: A CASE STUDY FOR RURAL ELECTRIFICATION

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Abstract— *The current study focuses on the design and optimization of a Hybrid Renewable Energy System (HRES) integrated with the grid, aimed at providing reliable and cost-effective electricity to rural areas near Jaipur, Rajasthan. The research leverages HOMER software for modeling a 500-kW HRES that includes solar photovoltaic (PV) systems, biogas-powered generators, and grid connectivity. Locally sourced biomass is utilized in strategically located biogas plants to enhance the sustainability of the energy system. The primary goal was to decrease the Levelized Cost of Electricity (LCOE). The economic viability of selling surplus energy to the power grid was assessed by simulations, which considered various metrics such as Internal Rate of Return (IRR), Return on Investment (ROI), Payback Period, and Levelized Cost of Electricity (LCOE). The findings demonstrate a reduction in Levelized Cost of Energy (LCOE) from Rs 10/kWh to Rs 7/kWh through the implementation of optimal Hybrid Renewable Energy Systems (HRES). Although there were minor decreases in IRR (Internal Rate of Return) and ROI (Return on Investment), the payback period remained stable, indicating that the economic feasibility is enhanced by selling surplus energy. These findings emphasize the importance of optimal Hybrid Renewable Energy System (HRES) designs in decreasing electricity expenses and encouraging the usage of sustainable energy in rural regions. This offers a practical approach for electrifying rural areas in Rajasthan and beyond. In present study machine learning was used to optimize the HRES system and the most effective combination was selected in which SPV, bio gas and grid all were in operational mode.*

Keywords— *Hybrid solar PV systems, Economic analysis of renewable energy, HOMER, Rural Electrification, smart grid*

I. INTRODUCTION

Solar energy is a leading sustainable energy source nowadays. Increasing global energy needs and environmental concerns make solar energy a potential and environmentally beneficial solution. Solar energy systems have grown rapidly due to a continual push to improve efficiency and production. Integrating current computational tools is crucial, signifying a new era of solar energy power production system efficiency and efficacy. Solar photovoltaic (SPV) system efficiency depends on design. These factors are linked to solar radiation intensity, clearness index, and grid connectivity. These factors determine system performance and output. Hybrid systems, which incorporate solar photovoltaic (PV) technology, can achieve combined benefits through careful design and optimization. To optimize wind energy extraction, these factors must be understood and improved. In renewable energy projects nowadays, strategic software tool use is common. The System Advisor Model (SAM) is reliable and versatile, providing extensive insights into solar, wind, and hybrid energy projects. Through simulations of renewable energy assets' dynamic behaviours during their lifecycle, SAM helps researchers and engineers make informed system configuration and operation decisions to optimise performance.

Current study designs and optimizes a HOMER-based Hybrid Renewable Energy System (HRES) for rural electrification in Jaipur, Rajasthan. This unique system integrates solar electricity with biogas from locally available bio-components into the electrical grid. The research is notable for establishing the technical viability of such a system for a 5000-kW electrical load and undertaking an economic analysis to

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optimize the system based on Levelized Cost of Electricity. Sustainable rural electrification has advanced due to this focus on technology innovation and economic sustainability.

II. LITERATURE REVIEW

Modern civilization relies on energy for economic growth, social well-being, and global connectivity [1]. Fossil fuels have been widely used to generate energy, but resource restrictions, growing populations, supply insecurity, and environmental concerns have created a worldwide energy crisis [1]. The 2022 Russian invasion of Ukraine has exacerbated these issues, casting a shadow over global energy dynamics and emphasizing the necessity for sustainable energy measures [2]. To reduce the environmental damage caused by fossil fuel-based power generation, the global narrative is shifting toward sustainable energy alternatives [3, 4]. Research suggests that renewable energy sources (REs), particularly solar and wind energy, could solve Rajasthan's energy problems [5, 6]. Many renewable energy research have focused on wind energy in western Rajasthan, despite its low potential [7-12]. Research shows hybrid renewable energy combinations in Rajasthan have promising possibilities [13-17].

The present study's specific energy generation emphasises Governorates' ability to satisfy their own energy needs, fostering decentralisation and energy self-sufficiency. Dadhich et al. [14] examined Rajasthan's renewable energy prospects using this approach. Studies have also examined solar potential in India, notably Rajasthan, including solar irradiation and equipment positioning in western Rajasthan for energy generation and Jaipur for transmission [18-21]. Researchers like Macedo et al. [22] have studied hybrid power generation, while Kitaneh et al. [23] have analyzed wind energy potential in several Palestinian locales. Yang et al.'s evaluations of solar installation efficiency in China have also examined environmental issues including shadowing [24-25]. Hybrid renewable energy systems (HRES) maximize complementary advantages to overcome the constraints of individual renewable energy sources. In quickly developing nations like China, solar-wind hybrid systems are becoming more important [24]. Yang et al. (2022) evaluated their feasibility and capacity optimization. Ganjei et al. (2022) examined the design and sensitivity analysis of an off-grid wind-solar power plant in rural Iran, emphasizing the need for diesel generators and battery storage for power continuity [25].

TABLE 1 SUMMARY OF THE RESEARCH PAPERS FOR HYBRID RENEWABLE ENERGY POWER PLANTS

Reference	Focus	Key Findings/Contributions
Yang et al. (2022) [24]	Feasibility of solar-wind hybrid systems in China	Optimized capacities for hybrid systems; emphasized importance in fast-developing nations.
Ganjei et al. (2022) [25]	Off-grid hybrid system in rural Iran	Importance of diesel generator and battery backup in hybrid systems for continuous power.
Amoussou et al. (2023) [26]	Solar PV, wind, hydrogen, and lithium battery hybrid system	Potential replacement for heavy fuel oil power plants.
Jani et al. (2022) [27]	Comprehensive evaluation of wind-solar plants	Evaluated through energy, exergy, economics, and environmental lenses.
Mao et al. (2022) [28]	Risk assessment in hybrid offshore wind-solar PV plants	Introduced a probabilistic linguistic environment for risk evaluation.
Meglic & Goic (2022) [29]	Impact of time resolution on hybrid systems	Time resolution can significantly affect energy losses.
Alghamdi (2022) [30]	Optimal power flow in wind and solar hybrid systems	Presented a new algorithm to enhance grid reliability and efficiency.

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Reference	Focus	Key Findings/Contributions
Silva & Estanqueiro (2022) [31]	Optimal design of utility-scale hybrid power plants	Provided insights into the design of large-scale hybrid systems.
Wang et al. (2023) [32]	Coordinated operation of hydropower with wind and solar	Conversion of traditional hydropower plants into hybrid pumped storage units.
Clark et al. (2022) [33]	Wind-solar hybrids for energy resilience	Emphasized the role of hybrid systems in energy security.
Tchaya & Djongyang (2023) [34]	Hybrid grid-tie system in Cameroon	Explored the potential of large-scale hybrid systems for energy supply.
Arnaoutakis et al. (2022) [35]	Wind-pumped storage combined with solar power	Case study on the integration of wind storage with solar in insular systems.

Beyond wind and solar, multiple renewable technologies are integrated. Amoussou et al. (2023) [26] optimized a complicated hybrid system including solar PV, wind, hydrogen, and lithium battery to replace heavy fuel oil power plants. Jani et al. (2022) [27] examined hybrid wind-solar plants' energy, exergy, economics, and environmental impact to assess their performance. Given renewable energy's uncertainty, HRES risk assessment is vital. In their 2022 methodology for assessing risks in hybrid offshore wind-solar PV projects, Mao et al. [28] stressed the complexity and probabilistic nature of risk assessments. Time resolution affects hybrid system energy losses, which is important for energy planning and management [29]. In line with optimization methodologies, Alghamdi (2022) [30] presented a novel algorithm for optimal power flow in wind-solar power systems, improving grid reliability and efficiency. Silva and Estanqueiro (2022) [31] optimized large-scale hybrid power plant design. Wang et al. (2023) [32] created hybrid pumped storage units by combining hydropower plants with wind and solar. Clark et al. (2022) [33] emphasize wind-solar hybrids' role in energy resilience and security. Tchaya and Djongyang's (2023) [34] study on large-scale hybrid grid-tie systems in Cameroon and Arnaoutakis et al.'s (2022) [35] case study on integrating wind-pumped storage with solar power in insular systems demonstrate HRES's growing global interest and applicability.

III. MATERIAL AND METHOD

The research technique used in this study is based on the understanding that renewable energy systems are greatly influenced by geographical and environmental factors, requiring accurate data collection. The study begins by identifying relevant renewable energy sources and then utilizes the HOMER program [36] to assess economic factors and get key indicators, as shown in Figure 1. In addition, simulation data for weather of the Jaipur for solar power facilities is generated using SAM software [37]. The procedure begins by collecting meteorological, energy, and economic data. The data is subsequently analyzed using HOMER to enhance the architecture of the Hybrid Renewable Energy System (HRES), guaranteeing complete dependence on renewable resources and meeting the entire electricity requirement. The proposed renewable energy solution is guaranteed to be reliable, efficient, and economically viable through the use of a systematic approach, as shown in the accompanying flowchart. As seen in the flow diagram, the proper design of system components were crucial in present study.

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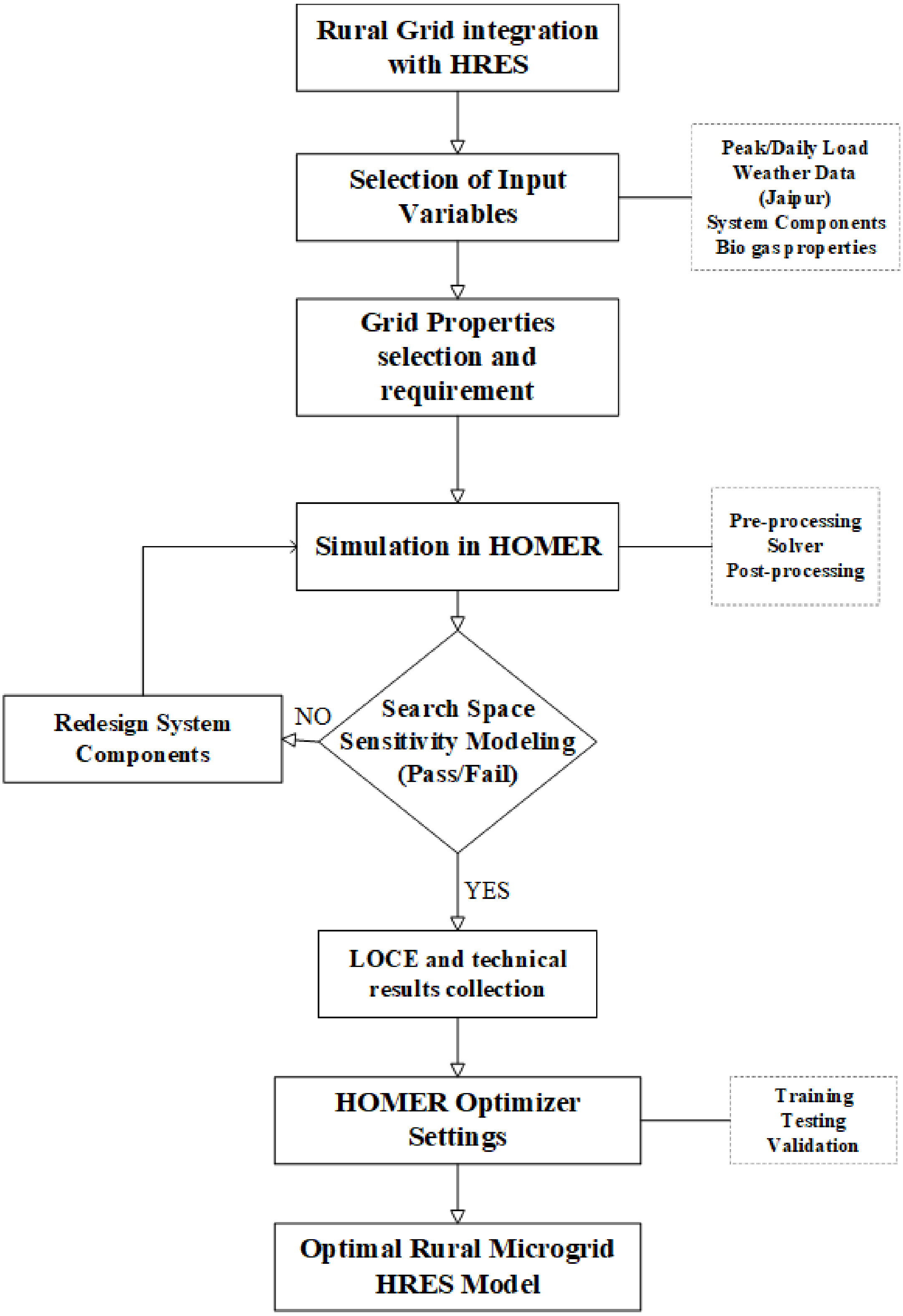

Fig. 1 Research flow diagram adopted in present investigation

IV. CASE STUDY REGION SELECTION

The focus of the study is to create a concise statement that addresses the energy requirements of rural areas by implementing a Hybrid Renewable Energy System (HRES). The task at hand involves developing a High Renewable Energy System (HRES) that can meet the 5853 kW power demand of ten villages (1. Goner 2. Siroli 3. Salgirampura 4. Vimalpura 5. Vidhani 6. Mathurawala 7. Jaichandpura 8. Rampura 9. Ramchandpura 10. Jeerota) selected for the development of the HRES system the google map image of the villages was shown in figure 2, while also seamlessly integrating with the Goner substation.

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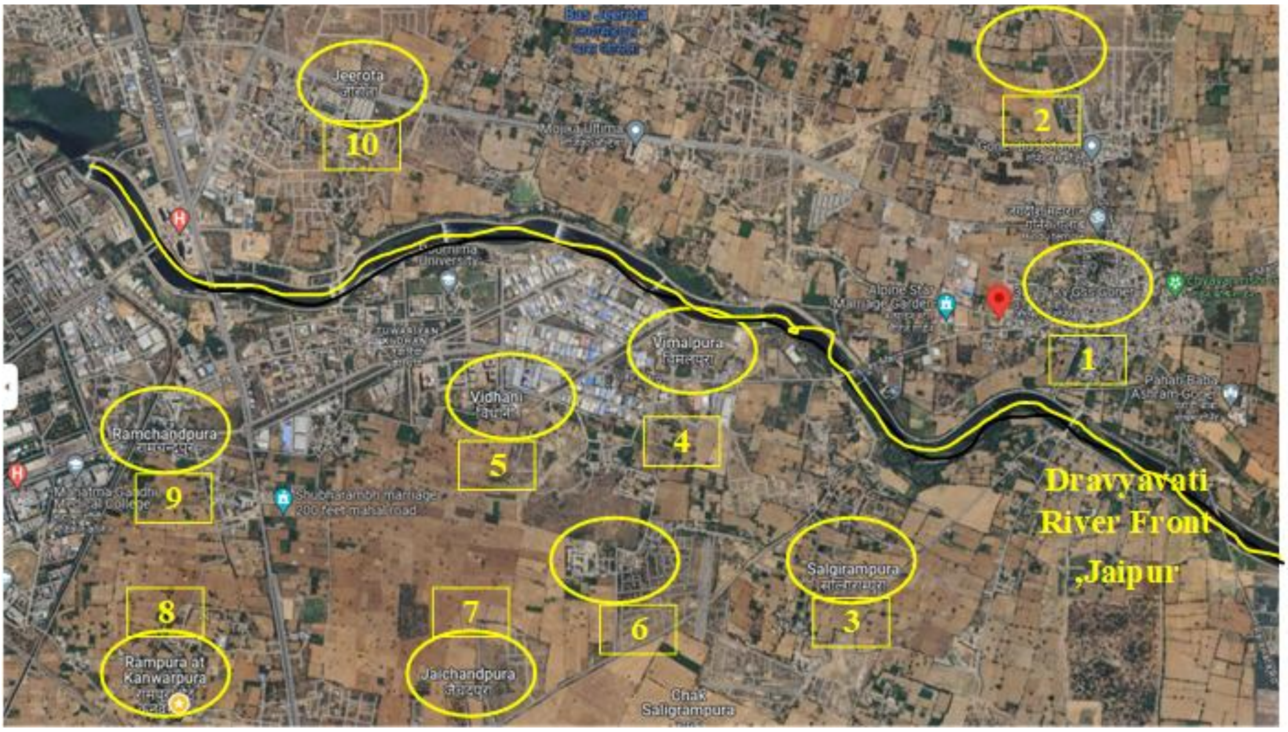

Fig. 2 Selection of villages for HRES design and optimization

The objective is to create a system that utilizes the area surrounding the Dravyavati River for solar installations, while making use of bio-organic components that are readily available in the local area for bio-gas generators. An analysis is conducted to determine the most economically advantageous alternative by modeling different grid selling capabilities. This analysis considers factors such as sustainability, economic feasibility, and alignment with local resources.

V. ELECTRICAL LOAD PROFILE

The initial electricity requirement for this study, as shown by the recorded load profile in figure 3 and monthly load profile in figure 4, illustrates monthly fluctuations in the electrical demand for the chosen settlements. The load peaks coincide with the hours of daylight, indicating the most efficient application of solar energy. The electrical energy usage patterns exhibit a similar pattern across the seasons, characterized by low electricity demand throughout the late night to early morning hours. The information is essential for developing a Hybrid Renewable Energy System (HRES) that effectively handles high and low demand periods, guaranteeing a dependable and environmentally friendly power supply for the ten villages all year round, with an average monthly power demand of 5853 kW.

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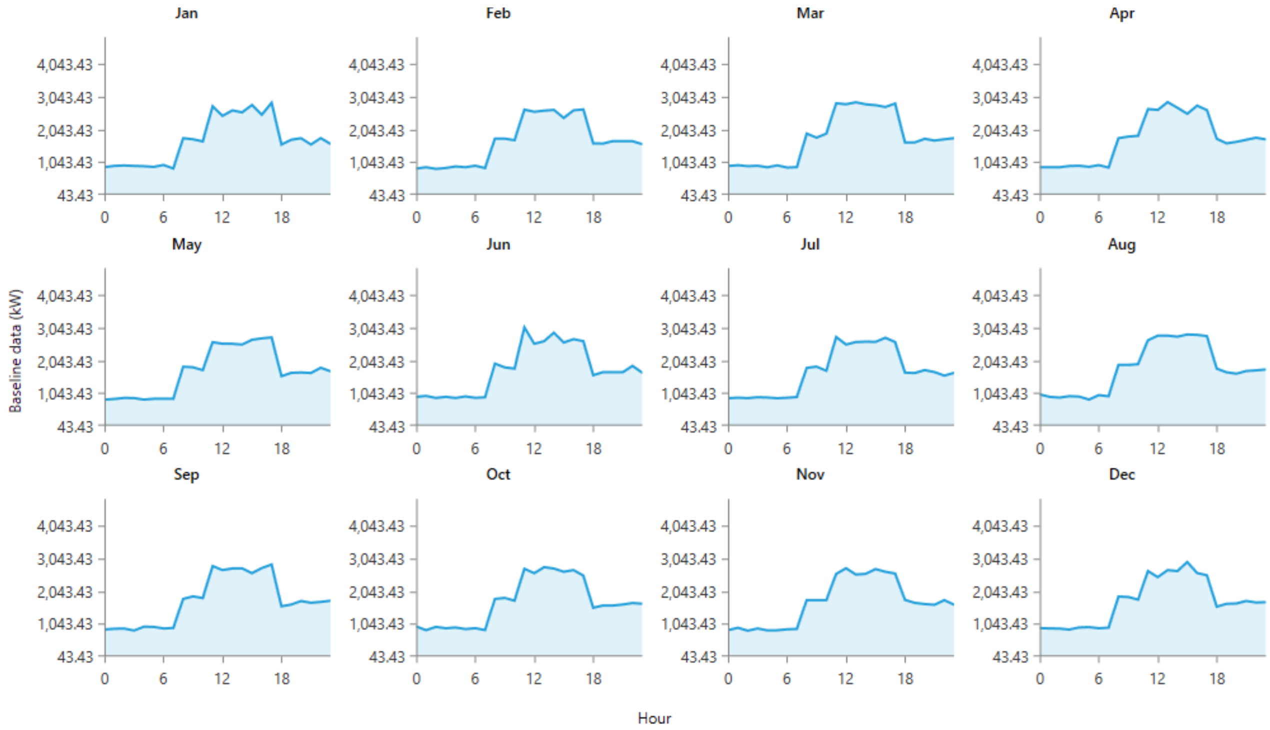

Fig. 3 profile plot of the electrical load of the ten villages selected in present investigation

The selected ten villages were mixed part of rural, industrial and commercial users of electricity demand. So the daily load profile was carefully collated and only rural electrical need was selected in this study.

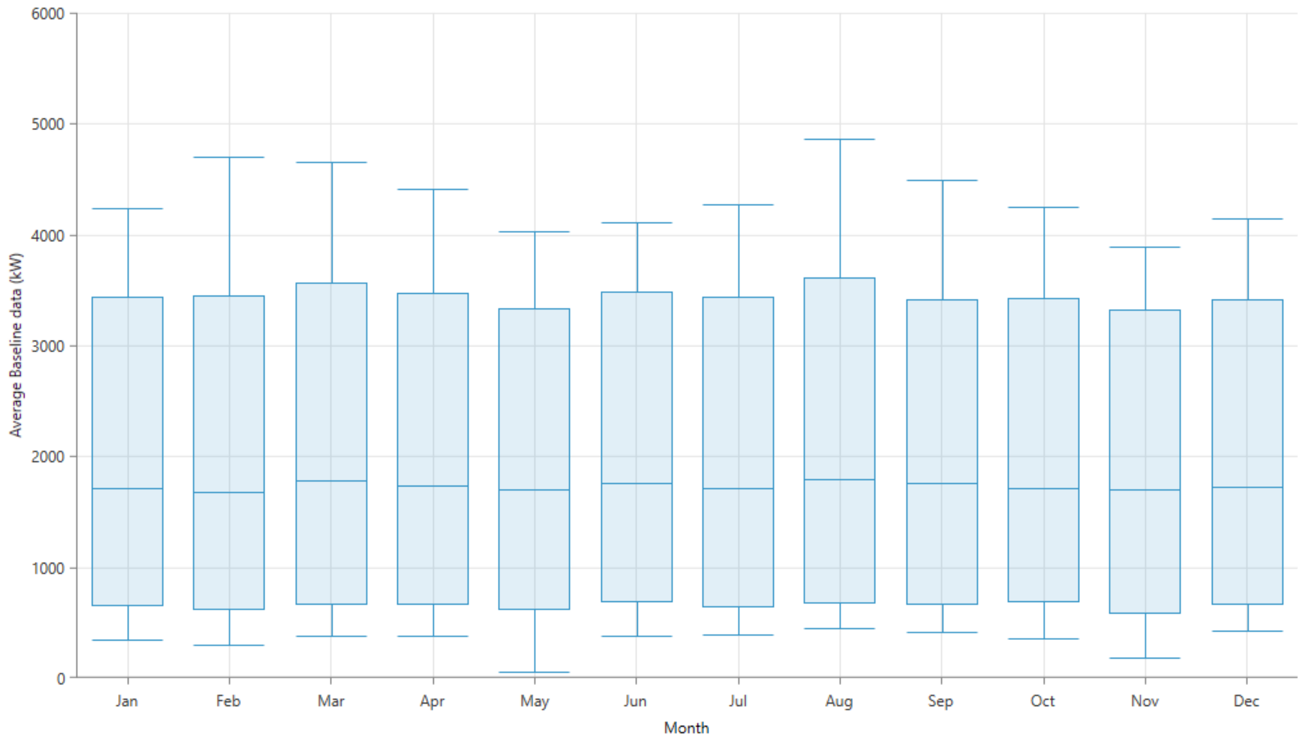

Fig. 4 monthly plot of the electrical load of the ten villages selected in present investigation

Figure 5 presents a D-Map study that demonstrates a spectral evaluation of electrical demand over a period of time. The presence of vibrant bands in the data indicates that there are fluctuations in energy consumption patterns throughout the year. These fluctuations are characterized by peaks and troughs, which signal that there are varying load requirements. The visual depiction is crucial for comprehending the temporal energy dynamics, which are vital for optimizing the performance of the Hybrid Renewable Energy System.

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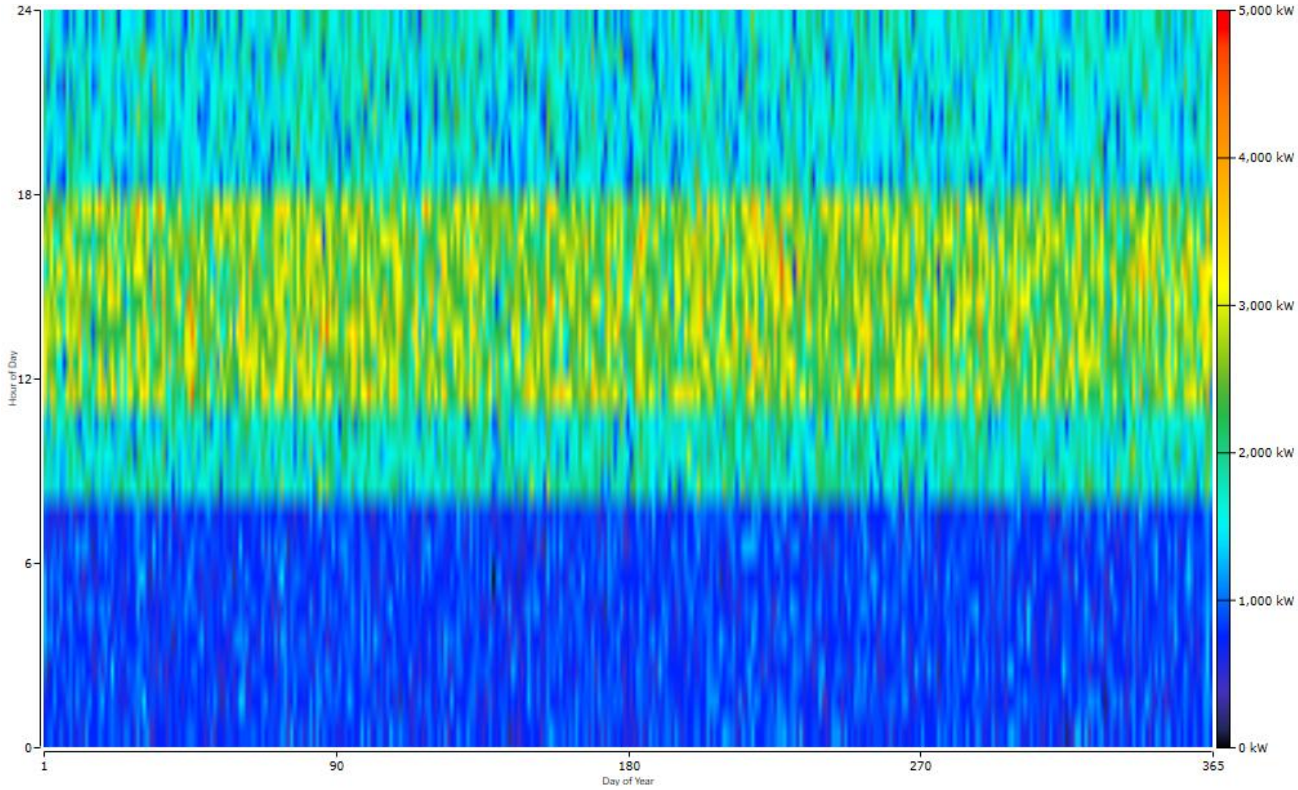

Fig. 5 D-map plot of the electrical load of the ten villages selected in present investigation

In present study the weather data was collected from SMA simulation software for Jaipur using ISHARE weather files and then used in HOMER software for simulation of the HRES system developed in present study. The solar radiation data and its clearness index data was shown in figure 6.

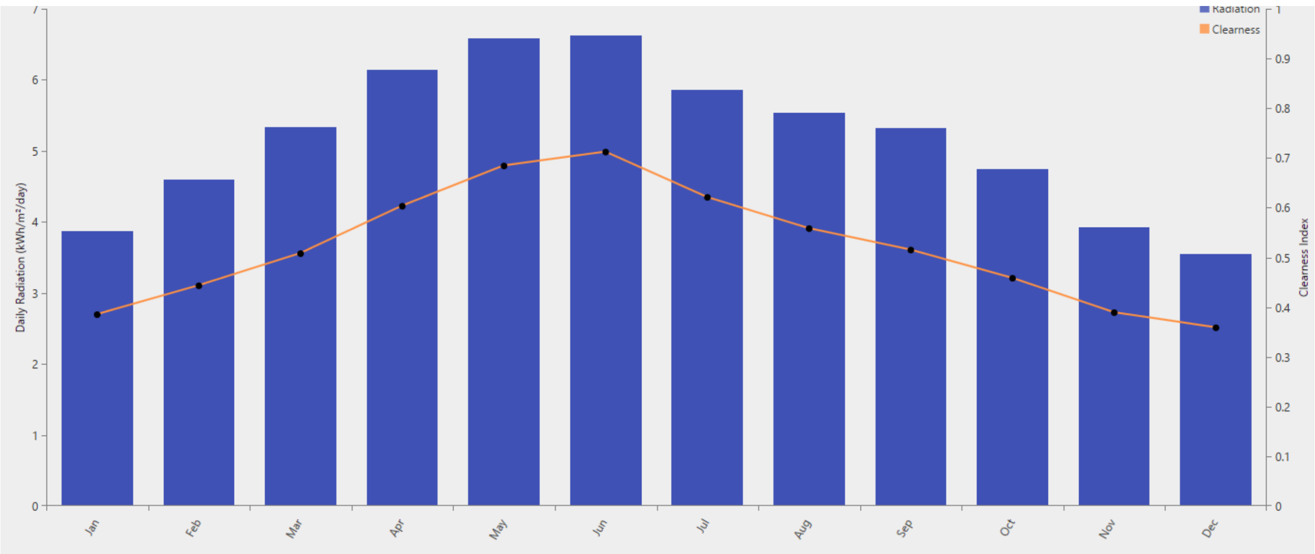

Fig. 6 Solar resource data for present simulation in HOMER

VI. SYSTEM COMPONENT DESIGN

The diagram depicted in Figure 7 illustrates the arrangement of the Hybrid Renewable Energy System (HRES) as simulated using the HOMER software. In order to fulfil the high electricity demand of the ten villages near Goner electrical sub division station, which reaches a peak of 5853 kW and requires a daily energy output of 50k kWh, the system incorporates a range of generating and conversion units.

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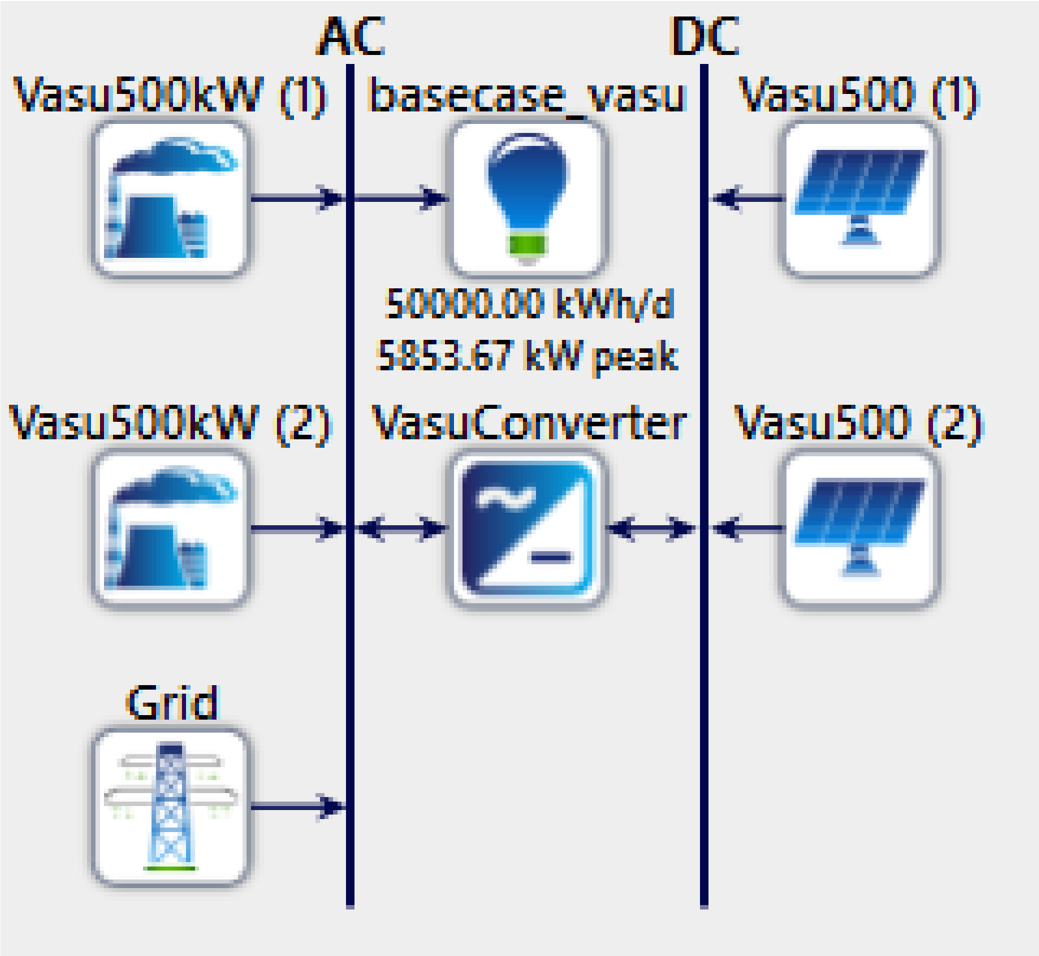

Fig. 7 Schematic diagram of the proposed HRES system

The system consists of maximum two Bio Gas generator sets each 500 kW capacity run on bio gas make by using waste Agro and animals waste in local region. Maximum two SPV photovoltaic array (each 500 kW capacity) gathers solar energy in this study the land cost was assumed nil because the solar power plants was proposed on the river front location which was totally free land for this type of projects, both solar power plants adding to the direct current (DC) side of the system. The components are connected to an inverter, which converts direct current (DC) into alternating current (AC) power. This conversion is necessary to make the power compatible with residential and commercial appliances. Furthermore, the system is linked to the local power grid (GridG0), functioning as a secondary power supply and allowing for the possibility of selling excess energy back to the grid. This diagram presents a detailed plan for the proposed Hybrid Renewable Energy System (HRES), showcasing the movement of energy from its production to its utilization. The detailed configurations of the system was present in table 2.

TABLE 2 CONFIGURATION OF SYSTEM COMPONENTS USED IN PROPOSED HRES SYSTEM

Component	Capacity (kW)	Price (/100 kW)	Reference
SPV-I	500	3.5 M	[39]
SPV-II	500	3.5 M	
Bio Gas-I	500	1.2 M	[40]
Bio Gas-II	500	1.2 M	
DC-AC Convertor	1000	0.5 M	-

As seen in table 2 ,the cost parameters was considered and technical parameters were considered as per literature review. The all possible HRES combinations made for present investigation present in table 3.

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TABLE 3 PROPOSED POSSIBLE COMBINATIONS OF HRES SYSTEM FOR PRESENT INVESTIGATION

Run	PV-I	PV-II	Bio-I	Bio-II	Grid	DC-AC
Unit	kW	kW	kW	kW	kW	kW
1	902	942	500	500	5500	953
2	1023	-	500	500	4500	487
3	-	733	500	500	4500	795
4	-	-	500	500	4500	-
5	1068	1022	500	-	5500	962
6	1068	1022	-	500	5500	962
7	1012	-	500	-	5000	484
8	1012	-	-	500	5000	484
9	-	1596	500	-	5000	1024
10	-	1596	-	500	5000	1024
11	-	-	500	-	5000	-
12	-	-	-	500	5000	-
13	988	1025	-	-	5500	972
14	1046	-	-	-	5500	489
15	-	1189	-	-	5500	467
16	-	-	-	-	5500	-

As seen in table 3 the last case was the base case in which only grid power was simulated in HOMER software and in remaining fifteen cases were proposed HRES cases with different system components having different capacity options to find the best optimal solution thorough year round simulation planning.

VII. RESULT AND DISCUSSION

The present study's analysis produced valuable findings concerning the energy procurement needs and the performance of the Hybrid Renewable Energy System (HRES) based on the Renewable Fraction. The monthly baseline power purchase requirement was determined, reflecting fluctuating levels of demand over the course of the year. The annual electricity purchases amounted to INR 18,249,385, inclusive of peak load costs and demand charges, which totaled INR 21,696,597.

TABLE 4 BASE CASE ELECTRICITY PURCHASE REQUIREMENT ON THE BASIS OF MONTHS (INR)

Month	Electricity Purchased	Peak Load	Electricity Charge	Demand Charge
1	1,531,142	5,094	13,060,638	1,782,782
2	1,356,750	5,500	11,573,077	1,925,000
3	1,599,075	5,500	13,640,108	1,925,000
4	1,507,856	5,307	12,862,007	1,857,416
5	1,521,460	4,846	12,978,057	1,696,157
6	1,519,525	4,936	12,961,551	1,727,706
7	1,530,069	5,134	13,051,486	1,796,792
8	1,603,571	5,500	13,678,463	1,925,000
9	1,521,388	5,395	12,977,438	1,888,326
10	1,534,793	5,114	13,091,783	1,789,918
11	1,475,722	4,673	12,587,909	1,635,722
12	1,548,034	4,991	13,204,729	1,746,773
Total	18,249,385	5,500	155,667,252	21,696,597

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The performance of the HRES was assessed using various Renewable Fractions, which varied from 60.42% to 0%. For each scenario, we computed the Net Present Cost (NPC) and the Levelized Cost of Electricity (LCOE). With a fall in the Renewable Fraction, there was an increase in both the NPC (Net Present Cost) and LCOE (Levelized Cost of Energy), which suggests that lesser integration of renewable energy leads to higher costs.

TABLE 5 COMPARISON OF DIFFERENT PARAMETERS FOR VARIOUS PROPOSED HRES SYSTEM

Run	**Renewable Fraction in HRES**	**Fuel**	**NPC**	**LCOE**
Unit	%	Tone/Yr	(In Billion)	INR
1	60.42	1251.41	1.31	5.45
2	54.43	1251.43	1.38	5.76
3	53.31	1251.43	1.39	5.82
4	47.54	1251.43	1.45	6.10
5	38.35	625.71	1.71	7.25
6	38.35	625.71	1.71	7.25
7	31.10	625.71	1.79	7.58
8	31.10	625.71	1.79	7.58
9	32.34	625.71	1.81	7.68
10	32.34	625.71	1.81	7.68
11	24.00	625.71	1.87	7.93
12	24.00	625.71	1.87	7.93
13	14.19	0.00	2.15	9.09
14	7.22	0.00	2.22	9.42
15	7.51	0.00	2.22	9.43
16	0.00	0.00	2.29	9.73

Note: Case 1 was Optimized and case 16 was base case

This trend highlights the economic significance of optimizing the use of renewable energy in the design of hybrid renewable energy systems (HRES). Furthermore, the analysis underscores the balance between the proportion of renewable energy and economic viability, underscoring the importance of maximizing the integration of renewable energy to attain energy solutions that are both cost-effective and sustainable.

VIII. CONCLUSION

The current study emphasizes the importance of Hybrid Renewable Energy Systems (HRES) in meeting the electricity requirements of rural villages. HRES provides a sustainable and economically feasible alternative to address the energy needs of isolated communities via careful planning and optimization. HRES, or Hybrid Renewable Energy System, guarantees a dependable power supply while reducing harm to the environment by combining various renewable energy sources like sun and wind with traditional grid infrastructure. The research demonstrates that by boosting the Renewable Fraction inside the Hybrid Renewable Energy System (HRES), there will be a decrease in the amount of power that needs to be purchased and a reduction in overall expenses. These findings highlight the crucial importance of HRES (Hybrid Renewable Energy Systems) in advancing the provision of electricity in rural areas, improving the availability of energy, and stimulating socio-economic progress in underprivileged regions. Advancing research and implementation in HRES technology is crucial for fully harnessing the potential of renewable energy in combating energy poverty and promoting sustainable development worldwide.

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