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Modelling, Simulation & Optimization of Renewable Energy-Based Hybrid Microgrid for Electrification of Rural Areas

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Abstract

Rural electrification in India faces persistent challenges due to unreliable grid connectivity, elevated transmission and distribution costs, and the geographical isolation of remote communities. Insufficient access to reliable electricity constrains economic development, educational opportunities, healthcare delivery, and overall quality of life in these areas. This study details the design and simulation of an off-grid, renewable-based hybrid micro grid for two rural villages: Khirgitola in Chhattisgarh, which has an electrification rate of 45%, and Akya in Madhya Pradesh, where grid access is intermittent and inadequate for daily needs. The estimated energy demands for Khirgitola and Akya are approximately 151 kWh/day and 132 kWh/day, respectively, with peak loads arising primarily from household appliances, lighting, irrigation pumps, and community infrastructure. To address these challenges, a hybrid micro grid integrating solar photovoltaic (PV) systems, battery energy storage, and a wind turbine is proposed. The system design prioritizes reliability, sustainability, and adaptability to local resource conditions. MATLAB-based simulations are utilized to evaluate technical feasibility, incorporating real-time solar irradiance and wind data. Additionally, a techno-economic analysis using HOMER software assesses various system configurations to determine the most cost-effective and environmentally sustainable energy mix. The findings indicate that a high proportion of renewable energy can be achieved through optimized resource allocation, substantially reducing reliance on conventional fossil fuels. The proposed hybrid micro grid enhances long-term energy accessibility, affordability, and resilience, thereby supporting sustainable rural development and improving socio-economic outcomes in underserved communities.

Keywords: Hybrid optimization model for electric renewable (HOMER), hybrid PV-wind system, net present cost (NPC), renewable energy, payback period

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INTRODUCTION

Electricity is essential for contemporary society, with demand rising in both rural and urban regions due to population growth [1]. However, reliance on fossil fuels for electricity generation results in significant greenhouse gas emissions and raises concerns regarding global warming [2]. In response, developed countries have implemented renewable energy policies that may serve as models for developing nations [3]. Sudibyo et al. (2021) investigated electrification strategies for remote villages in Indonesia by employing HOMER software and MATLAB to simulate photovoltaic (PV) arrays, wind resources, power converters, and energy requirements [4]. Alsagri et al. (2021) evaluated optimal systems for off-grid health clinics and recommended configurations based on the lowest Net Present Cost (NPC) [5]. Despite India's substantial solar and wind resources, rural electrification remains inconsistent. The western region receives approximately 5.41 kWh/m²/day of solar energy, and wind speeds range from 2 to 8 m/s, supporting the feasibility of small and medium-scale wind projects.

Chhattisgarh and Madhya Pradesh, despite their renewable resources, still face energy access challenges. In this study, the feasibility of electrification of two remote areas of Chhattisgarh (C.G.) and Madhya Pradesh (M.P.) was studied using HOMER software and modelled in MATLAB. This investigation suggested that the Hybrid Renewable Energy System (HRES) integrating battery storage, solar, and wind power can be implemented for off-grid electrification of the selected villages. As per our knowledge and belief, this is the first study to search an alternate source of electrification for the Khirgitola and Akya which are not connected with the main grid.

METHODOLOGY

Site Selection

In selecting appropriate sites for our study on renewable energy development, we have focused on two villages in Chhattisgarh and Madhya Pradesh, India: Khirgitola and Akya. Both villages exhibit unique geographic, demographic, and climatic characteristics pertinent to our research. Khirgitola is situated in the Dhamtari district of Chhattisgarh. The village's geographic coordinates place it within a region characterized by a subtropical climate, experiencing hot summers, a monsoon season, and mild winters. The topography is generally flat, which is conducive to infrastructure development. Agriculture is the primary occupation in the village, with a significant proportion of residents engaged in farming and related activities. The input parameters for the analysis were gathered from the CREDA Raipur Chhattisgarh and Madhya Pradesh Urja Vikas Nigam (MPUVN) and additional environmental data were obtained from the location-based database of the software.

Akya is located in the Neemuch district of Madhya Pradesh. The village has a total area of 129.71 hectares. The climate in this region is semi-arid, characterized by hot summers, moderate rainfall during the monsoon, and cool winters. The terrain is predominantly flat, with some undulating areas, making it suitable for agricultural practices.

Load Assessment

HOMER program automatically assesses power usage for housing demands in Akya & Khirgitola. The power usage load in both locations is as follows:

Akya uses an average of 131.45kWh/day with & maximum load of 13 kW, whereas Khirgitola consumes an average of 151.37 kWh/day & peak load of 14.35 kW. Figure 1 and 2 above show residential electricity consumption burdens in Akya and Khirgitola respectively. A PV-wind turbine hybridized off-grid system needs a number of components to perform properly. Furthermore, these components play an important role in cost analysis.

Assessment of Renewable Energy Potential

Based on the geographical and climatic conditions prevalent in many rural parts of India, several renewable energy sources are theoretically available, including hydro, biomass, solar, and wind. However, practical implementation is often limited by technical, economic, and environmental factors. For instance, while hydro power requires consistent water flow and suitable topography, many rural regions lack perennial water sources or elevation gradients. Similarly, biomass-based energy demands a regular and sustainable supply of agricultural or forest residue, which is either insufficient or already utilized for domestic purposes such as cooking. Due to these constraints, solar and wind energy emerge as the most feasible options for decentralized energy generation. Solar energy is particularly advantageous given India's high solar insolation throughout the year, while wind energy can be effectively harnessed in areas with favorable wind profiles and is useful to supply electricity when solar irradiance is low. Hence, this study focuses on assessing the viability and optimization of hybrid solar-wind systems tailored to the local resource availability, load demand, and economic feasibility.

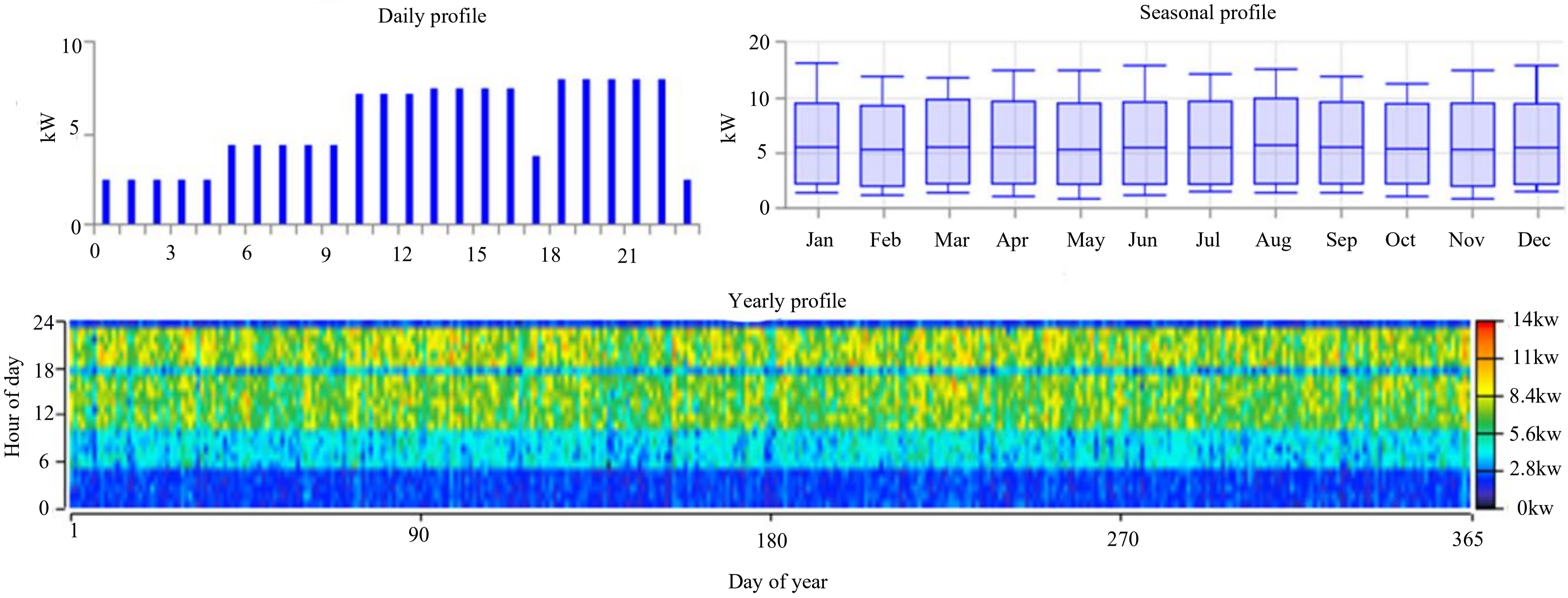


Figure 1. Average electricity demand in the Akya village.

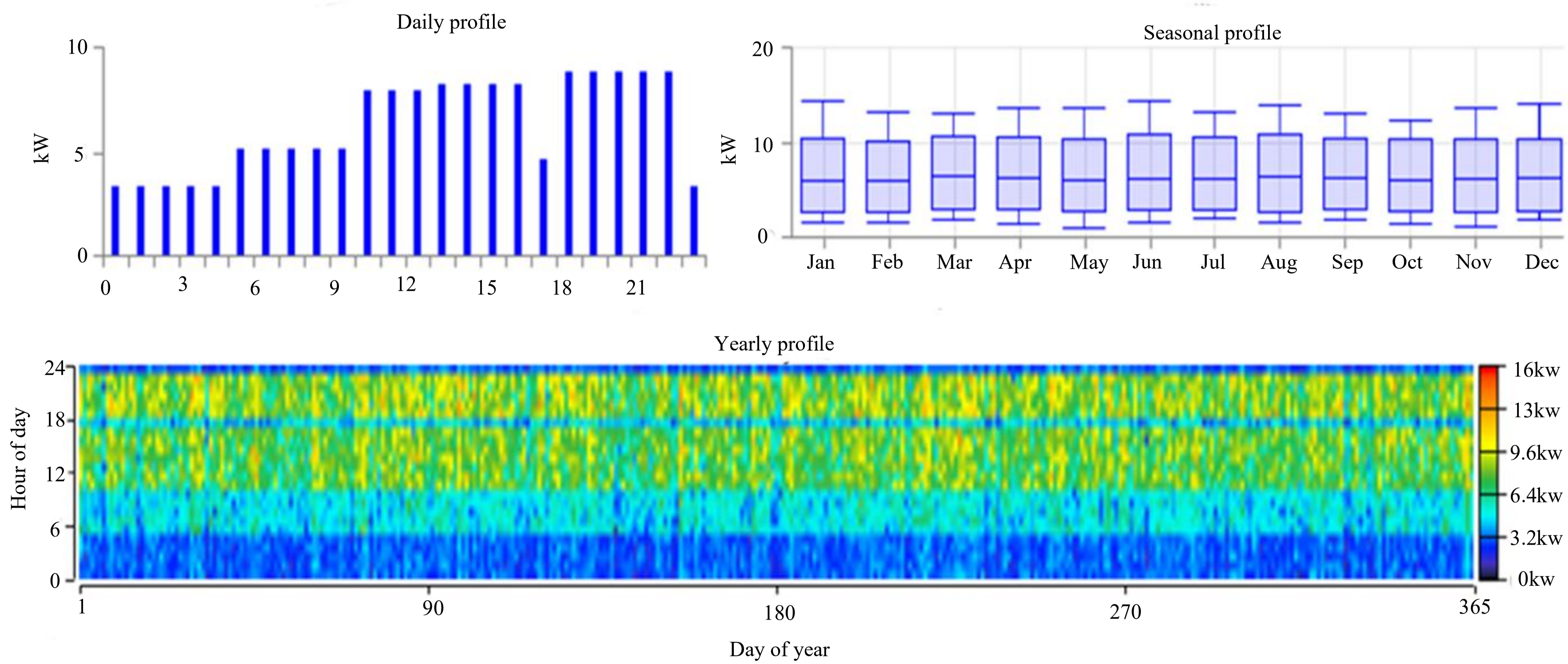


Figure 2. Average electricity demand in the Khirgitola village.

Table 1. Summary of simulation input parameters.

Category	Input parameter	Khirgitola	Akya	Data source
Solar Energy	Avg. solar irradiance(kwh/m2/day)	5.24	5.5	National solar energy database
	Solar resource potential	High	High	
Wind Energy	Avg. annual wind speed(m/s)	3.38	3.29	NASA Surface Meteorology and Solar Radiation
	Wind resource	Moderate	Moderate	
Hybrid System Inputs	System Components	PV Panels, Wind turbine, DC-DC converter	PV Panels, Wind turbine, DC-DC converter	System Design
Battery	Normal voltage(volt)	12	12	
	Capacity Ratio	0.335	0.335	
	Maximum Capacity	200Ah	200Ah	

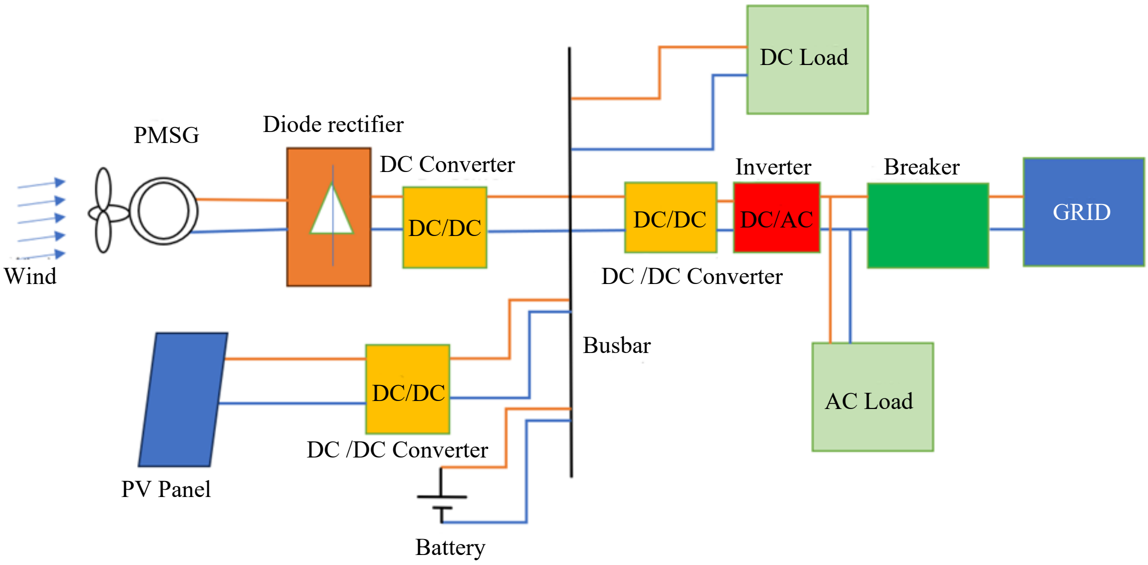


Figure 3. Hybrid system based on microgrids and renewable energy sources. PV stands for photovoltaic; PMSG for permanent magnet concurrent generator; AC for alternating current; and DC for direct current (Regenerated from Figure 2 of Baseem Khan, 2023) [6].

Hybrid Energy

The schematic diagram of the proposed system offers a glimpse into its architecture. A wind turbine (WT) converts wind energy into alternating current (AC) electricity, while photovoltaic (PV) panels generate direct current (DC), which is managed by a DC-DC converter. Wind energy plays a crucial role in addressing the global energy crisis and combating climate change by reducing greenhouse gas emissions, including CO2, SO2, and NOx. Furthermore, it cuts costs and lessens reliance on fossil fuels. Figure 3 illustrates the schematic of the PV-wind hybrid microgrid system.

System Modeling With MATLAB

Mathematical Modeling

Despite their remarkable cleanliness and efficiency, renewable energy sources pose significant environmental challenges. A hybrid system surpasses one that relies solely on renewable energy [7]. The performance and analysis of wind turbines (WT) are largely dependent on their geometric design, which determines the key performance parameters. The overall power coefficient (CP) indicates the productivity of the entire wind system. The output power of the WT in the final stage is defined as [8].

$$P_{AV} = {}^{1}\!/_{2}\,\rho A U_{\infty}^{3} \quad (1)$$

$$T = m(U_{\infty} - U_{W}) \quad (2)$$

$$T = m(P_{u} - P_{d}) \quad (3)$$

Equation (3) may be written as:[6]

$$T = \frac{1}{2}\rho A(U_{\infty}^{2} - U_{w}^{2}) \quad (4)$$

Where Pd & Pu are the corresponding downstream and upstream pressures, corresponding. The rate of flow of mass is replaced in Equation (2), producing the given outputs.

$$T = \rho URA(U_{\infty} - U_{w}) \quad (5)$$

(4) & (5) can be utilized to denote the speed of the winds at the blade plane as follows: an average of both downstream and upstream wind speeds.

$$U_{R} = \frac{(U_{\infty} - U_{w})}{2} \quad (6)$$

The drop in wind speed due to friction is indisputable. Therefore,

$$a = \frac{(U_{\infty} - U_{w})}{U} \quad (7)$$

This can be shown as,

$$U_{R} = U_{\infty}(1 - a) \quad (8)$$

$$U_{w} = U_{\infty}(1 - 2a) \quad (9)$$

To maintain stability, the width of the fluid field must expand when its speed decreases, similar to how the torque generated by the turbine vanes increases when they spin in response to a sudden drop in the rotor plane's load. The power produced by the rotor is calculated as the product of thrust and velocity across the rotor plane. According to equation (4), the resulting power is expressed as follows;

$$P = {}^{1}\!/_{2}\,\rho A(U_{\infty}^{2} - U_{w}^{2})U_{R} \quad (10)$$

By substituting equation (8) & (9) from equation (10) we got equation (11),

$$P = 2\rho Aa(1 - a)2U_{\infty}^{3} \quad (11)$$

The capability of WTs to draw out electricity influences how much load it can generate.

$$P = \frac{1}{2}\rho AU_{\infty}3C_{p}(a) \quad (12)$$

Equations (11) & (12) are equivalent; the outcome's power coefficient is

$$C_{p}(a) = 4a(1 - a)^{2} \quad (13)$$

The torque of the turbine vanes is represented as:

$$T = \frac{1}{2}\rho AU_{\infty}2RCT(a) \quad (14)$$

Economic Analysis with Homer

Economic evaluation is a crucial aspect of designing hybrid energy systems, ensuring financial sustainability and feasibility. In this study, HOMER Pro (trial version) has been utilized to estimate the overall cost of holding, with inceptive investment, working & repair costs, fuel expenditures & component replacements over the system's lifetime. The software employs a life cycle cost assessment approach to determine key economic points of reference, such as Net Present Cost (NPC), payback period, and Levelized Cost of Energy (LCOE), providing valuable insights into long-term viability. Additionally, HOMER Pro allows for sensitivity analysis, evaluating the impact of variations in fuel prices, interest rates, and component costs on system performance. By integrating both economic and technical parameters, this tool facilitates the selection of optimized hybrid energy solutions, making it effective for sustainable energy planning and rural electrification.

Payback Period

It is defined as the time that is required for the total savings or revenue produced by the system to recover the initial capital investment [9,10].

It is defined as,

$$\text{Payback Period} = \frac{\text{Total initial investment}}{\text{Net Annual Savings}} \tag{15}$$

$$\text{Net Annual Savings} = \text{Revenue Generated} - \text{Operating \& Maintenance costs} \tag{16}$$

SIMULATION AND RESULTS

MATLAB simulations and HOMER software were utilized to evaluate the economic and technical feasibility of a hybrid energy system comprising PV, wind turbines, and battery storage. The primary objectives of the evaluation were cost minimization and reduction of environmental impact. Key performance indicators considered in HOMER-based analysis included Net Present Cost (NPC), Cost of Energy (COE), total energy generation, and renewable energy fraction.

MATLAB Simulation and Results

MATLAB (student version) Prior to optimization, the hypothetical model is simulated using software. Figure 4 shows the model of PV-wind hybrid system.

Due to escalating environmental concerns, there's growing interest in renewable energy sources such as wind and solar, which are experiencing rapid advancements. Technological developments in renewables have increased the proportion of clean energy used to satisfy the growing demand for power. Although, solar and wind energy alone can't meet the world's entire energy needs. Combining them improves the reliability of the power supply. Hybrid wind and solar power systems, not connected to the main grid, are mainly used for individual applications. In these systems, a discrete PWM generator (VR) controls the bipolar junction transistor (BJT). Transforming regulators convert DC input voltages into modified voltages, which are then used to power devices through a MOSFET/BJT switch.

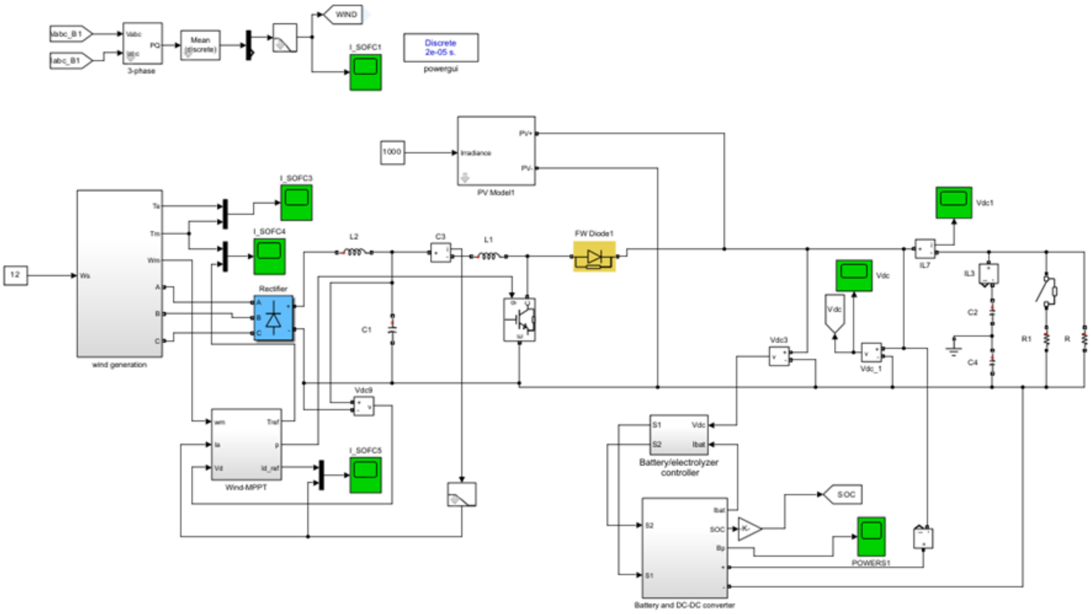


Figure 4. PV-wind hybrid microgrid system.

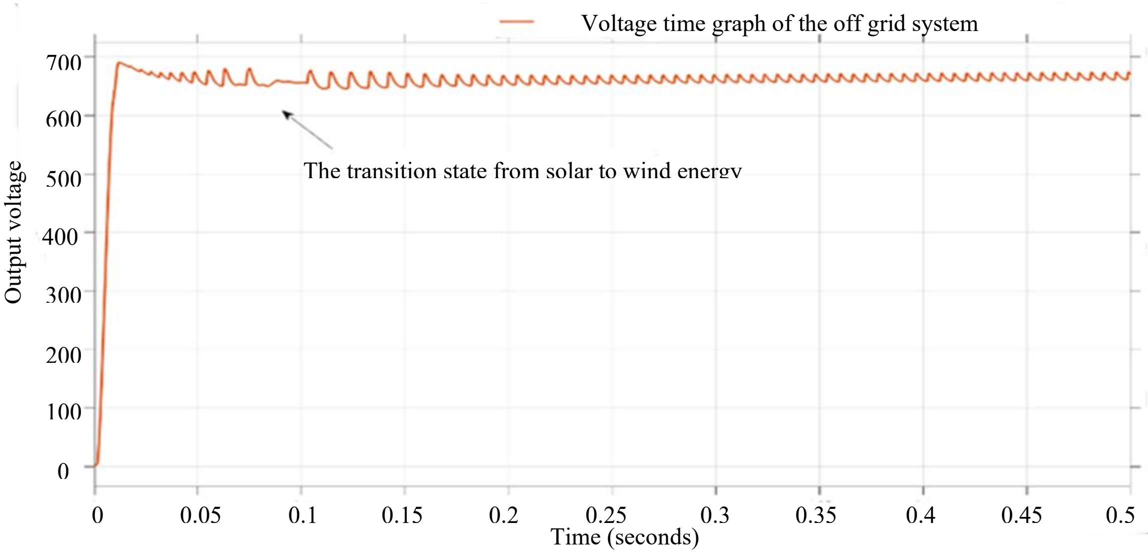


Figure 5. DC voltage- time graph of HMGS (time in seconds on x-axis and voltage in volts on y-axis).

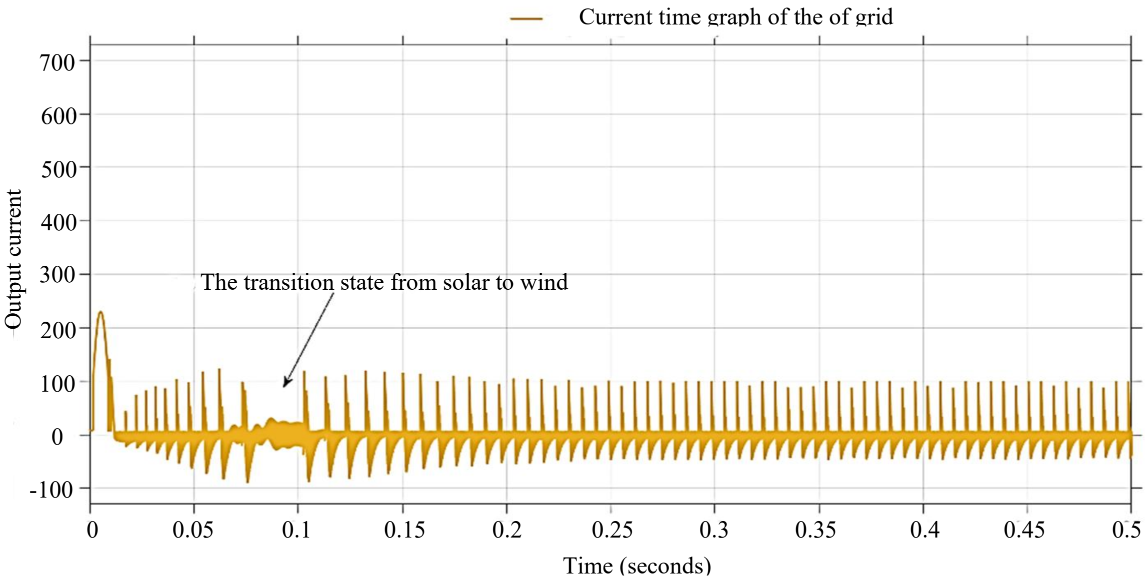


Figure 6. AC Output current- time graph of HMGS (time in seconds on x-axis and current in amperes on y-axis).

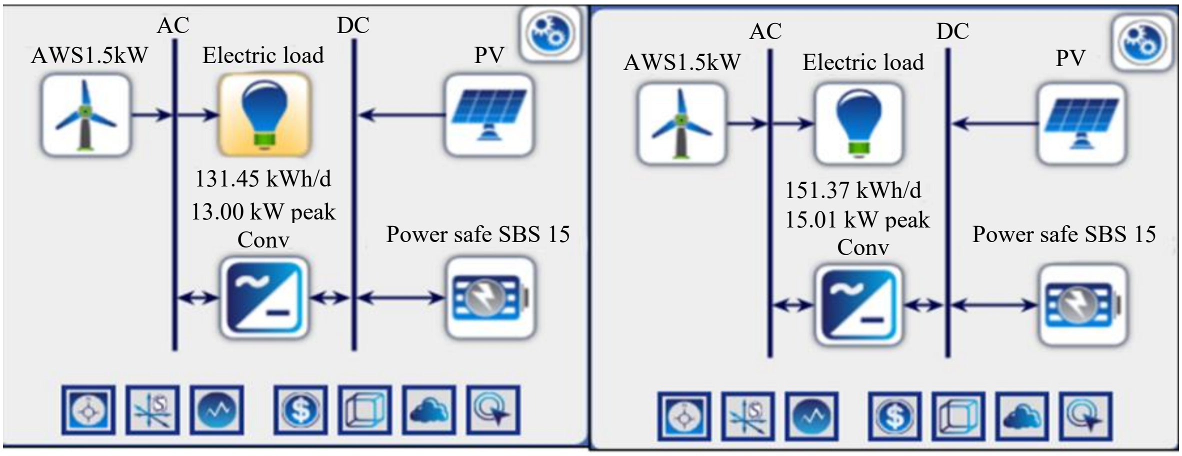
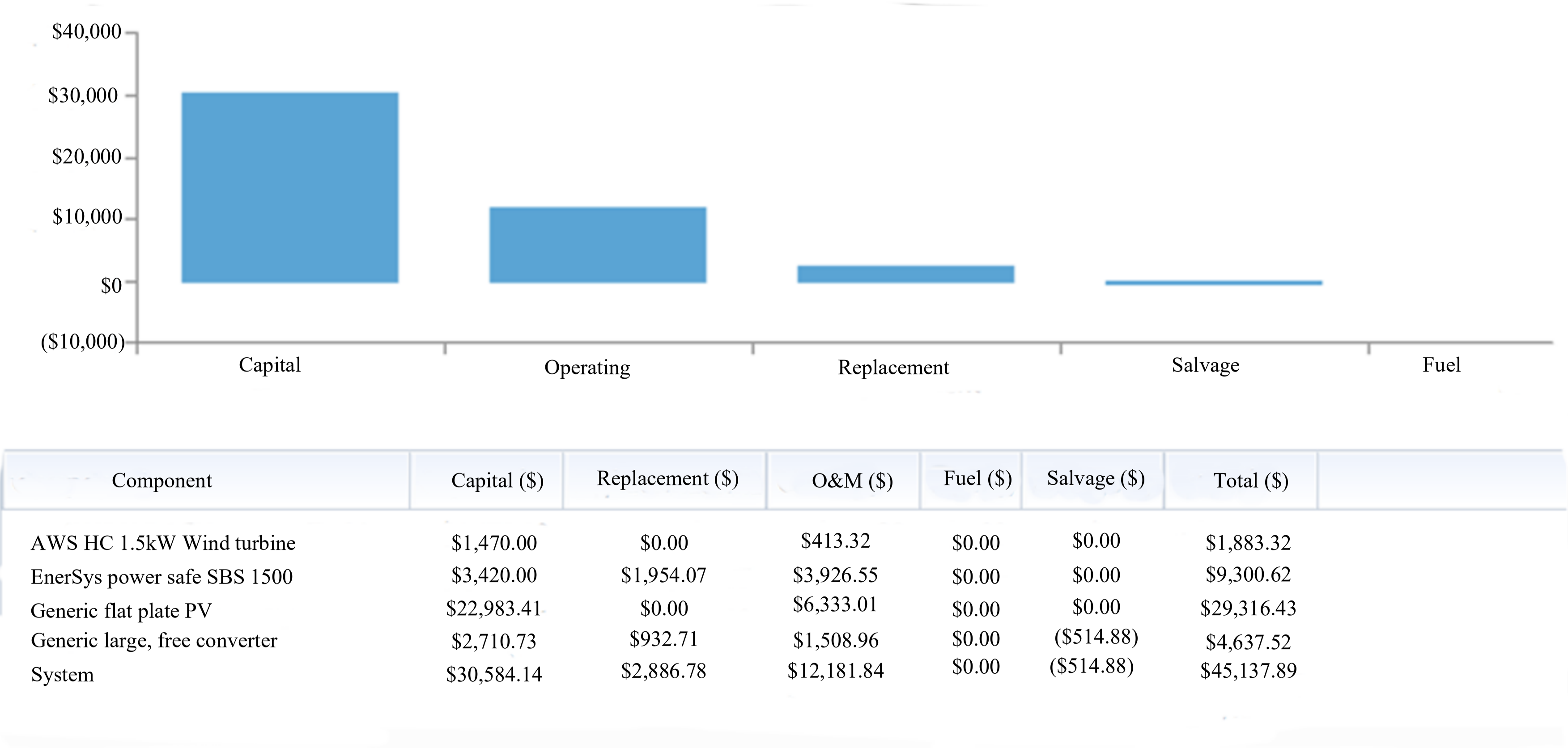
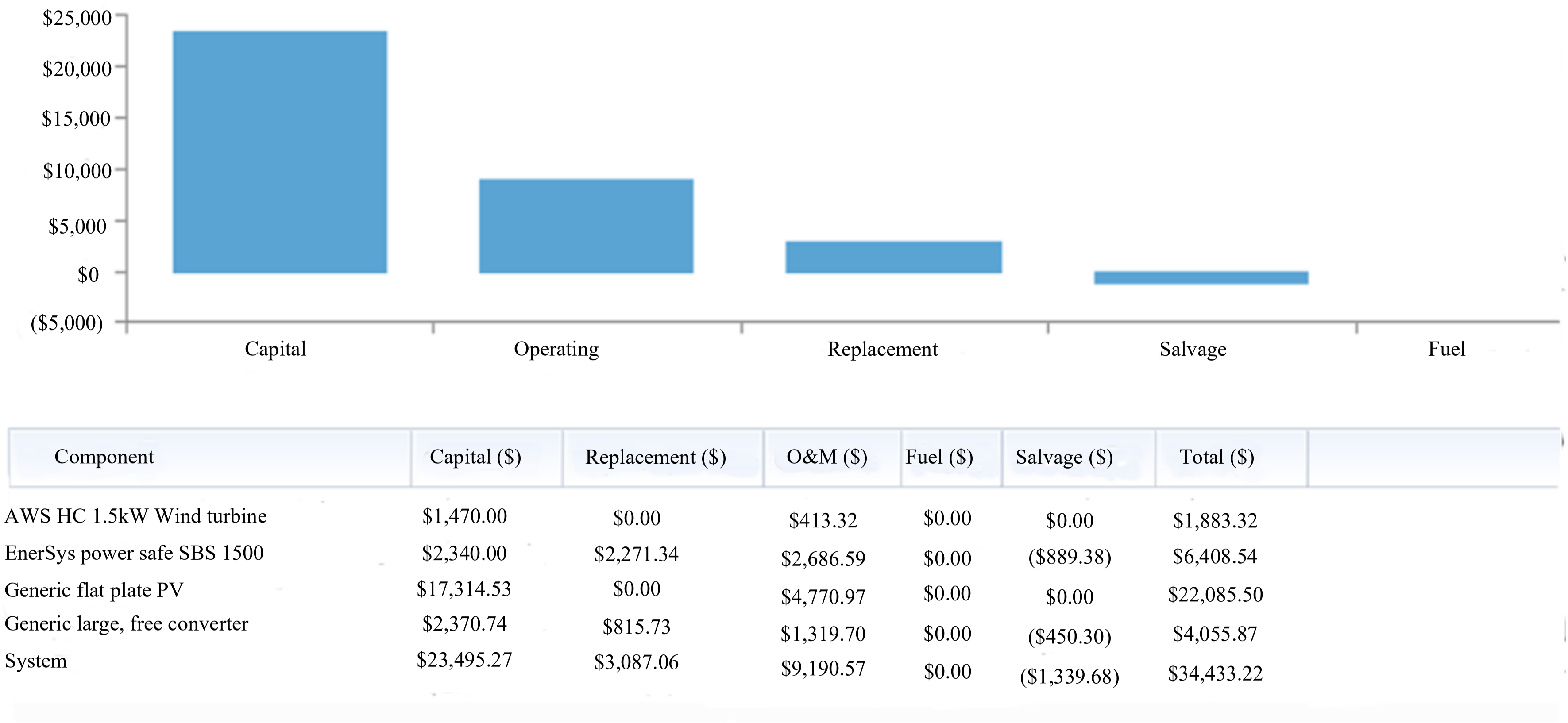


Figure 7. Projected PV & wind turbine standalone system for Akya and Khirgitola.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
AWS HC 1.5kW Wind turbine	$1,470.00	$0.00	$413.32	$0.00	$0.00	$1,883.32
EnerSys power safe SBS 1500	$3,420.00	$1,954.07	$3,926.55	$0.00	$0.00	$9,300.62
Generic flat plate PV	$22,983.41	$0.00	$6,333.01	$0.00	$0.00	$29,316.43
Generic large, free converter	$2,710.73	$932.71	$1,508.96	$0.00	($514.88)	$4,637.52
System	$30,584.14	$2,886.78	$12,181.84	$0.00	($514.88)	$45,137.89

Figure 8. Estimated total expense for the hybrid energy setup in Khirgitola village.



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EnerSys power safe SBS 1500	$2,340.00	$2,271.34	$2,686.59	$0.00	($889.38)	$6,408.54
Generic flat plate PV	$17,314.53	$0.00	$4,770.97	$0.00	$0.00	$22,085.50
Generic large, free converter	$2,370.74	$815.73	$1,319.70	$0.00	($450.30)	$4,055.87
System	$23,495.27	$3,087.06	$9,190.57	$0.00	($1,339.68)	$34,433.22

Figure 9. Estimated total expense for the hybrid energy setup in Akya village.

Solar Electricity Production

The graph shown below in Figure 5 and 6 depicts the PV system's MATLAB model. In the given System, the calculated voltage in open circuits (Voc. environment) was 28.4 volts, and the PV array's saturating period is 0.04 seconds [6].

MPPT Method

The authors applied MPPT P&O technique for their investigation. It is connected with both the buck/boost and boost converters that are used & the IGBTs in the circuits have an operational cycle of 0.5. It generates a frequency of roughly 5000 Hz by PWM.

Developed HMGS Simulation Model

The graphic above depicts the created HMGS's MATLAB Simulink model. To ensure a uniform output voltage, the device that regulates the main switch on and off times voltage supplied that is generated.

HOMER Simulation and Results

Framework Setup

The suggested PV-wind turbine system structures possess the precise parameters as well as expenses for every prearranged area. The system attached with the primary connections is made up of PV panels, turbines for wind power, converters, as well as batteries, displayed in Figure 7. Techno- economic prototypes are performed using HOMER via the suggested plan first assembled as per the defined configuration. The result of cost analysis are shown below in Figure 8 and 9.

CONCLUSION

This study details a complete design, simulation, and techno-economic assessment of a hybrid solar-wind microgrid for providing off-grid electricity to Akya (Madhya Pradesh) and Khirgitola (Chhattisgarh). The HOMER-based analysis reveals that the best setup differs depending on the location, significantly affecting the Net Present Cost (NPC) and Cost of Energy (COE). For Akya, the NPC is $34,433.22 (₹2,926,824), with a COE of ₹4.62/kWh, whereas Khirgitola's system has an NPC of $45,137.89 (₹3,836,720) and a COE of ₹5.26/kWh. Both systems produce excess energy—12,253 kWh/year for Akya and 19,760 kWh/year for Khirgitola—which can be sold to the government at ₹3/kWh, potentially generating ₹36,759/year and ₹59,280/year, respectively. Over two decades, this equates to a total income of ₹7.35 lakh for Akya and ₹11.85 lakh for Khirgitola, supporting the socio-economic advancement of these communities.

The payback period for the hybrid system, calculated using equations (15) and (16), is approximately 11.5 years for Akya and 12.5 years for Khirgitola. In comparison, removing the wind turbine shortens the payback period to 10.5 years and 11.5 years, respectively. Despite the slightly higher cost due to low wind speeds (3.29 m/s for Akya and 3.38 m/s for Khirgitola), incorporating wind is crucial for improving system reliability during times of low sunlight. Therefore, the compromise between a slightly longer payback period and increased supply stability makes the hybrid system a practical and dependable choice, particularly for essential rural applications.

However, given the economic considerations, integrating wind power might be reevaluated or substituted to reduce the payback time. Future implementations could investigate connecting to the main grid as a backup during periods of insufficient solar energy, thereby optimizing costs without compromising energy reliability. Furthermore, future research could focus on hardware implementation, adaptive MPPT algorithms, and battery optimization to enhance efficiency. The study confirms that renewable microgrids not only ensure sustainable rural electrification but also promote energy security, economic resilience, and long-term community development in remote areas.

LIMITATIONS

Low Wind Resource Availability

Due to the relatively slow average wind speeds at Khirgitola and Akya (3.29–3.38 m/s), wind turbine performance is compromised. Consequently, costs are higher, the annual energy yield is lower, and the payback period is somewhat longer than with solar energy alone.

Solar Energy Variability and Data Reliability Constraints

A range of system parameters, such as solar irradiance, wind patterns, load changes, and economic data, were obtained from databases or modeled using MATLAB/HOMER software. Without long-term, on-site measurements, the accuracy of predicting actual performance is compromised.

Economic Assumptions May Change Over Time

The NPC, COE, and payback calculations rely on current market prices. Economic viability is subject to change due to shifts in interest rates, government support, import tariffs, and component expenses.

FUTURE SCOPE

Further research could focus on implementing the hybrid microgrid in a real-world setting to confirm the simulation findings. Setting up a pilot project in a village and observing its performance throughout the year would provide more reliable data regarding system reliability and practical hurdles.

Further investigation into battery optimization is recommended. Assessing innovative storage solutions, creating more precise degradation models, and incorporating sophisticated Battery Management Systems (BMS) can extend system longevity and minimize long-term expenses.

The energy mix offers potential for expansion. Integrating biomass, micro-hydro, or hydrogen-based backup systems, or even investigating grid-as-backup solutions, can enhance system reliability when renewable energy sources are limited. Future research should focus on scalability and policy integration. Developing flexible design frameworks, incorporating financial incentives, and utilizing smart metering and demand-side management can facilitate the effective replication of this model in other rural areas.

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