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Research Article

An Assessment and Design of a Distributed Hybrid Energy System for Rural Electrification: The Case for Jamataka Village, Botswana

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This research focuses on an assessment and design of a hybrid Photo Voltaic (PV)-wind system for rural electrification in Jamataka village, Botswana. The assessment revealed the most pressing factors for the need for reliable energy and the issues that the village community had with existing electricity sources. Hybrid Optimization of Multiple Energy Resources (HOMER) software was used to perform all the hybrid system configurations, simulations, and selections. The assessment research was carried out using questionnaires and physical data collection on site. With a peak load of 27.31 kW, the annual average demand is 165.29 kWh/day. The results show that the PV/wind/battery system generates the most economic and technical benefits, as measured by the Net Present Cost (NPC). Due to the high initial expenditures on renewable energy systems, the Levelized Cost of Energy (LCOE) of the system is 65 percent higher than the present energy cost in Botswana for households and 57 percent higher for companies. The International Renewable Energy Agency's global report of renewable energy generation costs between 2010 and 2020 revealed a significant decrease, with utility-scale solar PV costs falling by 85% and onshore wind costs falling by 56 percent. As a result, the LCOE decreases as the cost of renewable energy decreases. Subsidies for renewable energy systems, on the other hand, can significantly reduce the LCOE.

1. Introduction

The electricity challenges faced by remote communities such as geographical constraints, economic, social, and cultural challenges are well known and documented [1–5]. Due to the high initial costs and intermittency of renewable energy sources like solar and wind, most renewable energy hybrid systems have design issues. Adding a diesel generator to the renewable energy hybrid systems will be an efficient option to boost system reliability [6]. To minimize the high initial costs associated with renewable energy power systems, costs associated with manufacturing battery storage systems and renewable energy technologies should be minimized [7]. Globally, about billion people are estimated to be without electricity, with grid extension challenges being one of the key contributing factors [8]. Fossil fuels, which accounted for nearly 80% of global energy in the last century, are fast depleting because of rising energy demand due to economic and population growth. As a result of this heavy reliance on fossil fuels, greenhouse gas emissions have increased, contributing to global warming and posing a serious threat to ecosystems and global health [9, 10]. However, the continued reduction in costs of renewable energy technologies such as solar, wind, and biomass technologies has also stimulated interest toward renewable energy sources [11–13]. Apart from cost benefits, renewable energy off-grid hybrid systems have other advantages, such as boosting local businesses, reducing pollution, and generating employment [5].

The challenges of energy provision in rural Botswana, as well as the impediments to the application of new technology in the energy industry, include uneven distribution of renewable energy resources, untapped solar potential, excessive heat affecting solar output production, human resource obstacles such as a low number of unskilled workers, and issues such as power theft arising from poverty [14].

Many studies have been undertaken on rural power systems, with most similar ones focusing on feasibility and techno-economic analysis. However, no similar study has been conducted in this rural location and the real-time data collection was captured. A feasibility study of a PV-wind hybrid power system for electrification of a rural village in Ethiopia, with fuel cells and rechargeable batteries as backups, produced different feasible alternative solutions with a small range of LCOE, much better than the previous generator set backup hybrid PV-wind system [15]. An economic evaluation study on solar hybrid energy systems for the Salalah region in Oman with approximated radiation ranging from 4.8 kWh/m^2/day to 7.4 kWh/m^2/day revealed that despite the huge quantity of pollution produced by the standalone generator, which is followed by the PV/generator set/wind/battery configuration, the PV/generator set/wind/battery design has the lowest energy cost when compared to the PV/wind/battery configuration and the stand-alone generator [16]. A techno-economic comparative analysis of renewable energy systems for a case study in Zimbabwe showed that a PV-wind hybrid system offers the most economic benefits, as measured by NPC and Pay Back Period (PBP) and the best operating efficiency [17]. Meanwhile, an optimization and techno-economic analysis of a photovoltaic/wind/battery/diesel system in northern Nigeria were carried out using the MATLAB environment for simulations and a genetic algorithm for optimization, with results indicating that the optimized system was more cost-effective and environmentally friendly than diesel generator and grid extension systems in the region [18]. The researchers also concluded that solar PV-based renewable hybrid systems play an important role in ensuring that rural communities in sub-Saharan Africa have access to reliable, sustainable, and modern electricity [18]. Ahmed, Albarawy, and Ibrahim [19] proposed a genetic algorithm to find the optimal sizing of PV/wind/battery/diesel generator with the goal of lowering levelized cost of energy and increasing reliability. They found that the LCOE decreases as design parameters increase and that average wind speed is inversely proportional to the LCOE of the location under study. Canziani, Vargas, and Gastelo-Roque [20] investigated the technical features including installation, operation, and social implications of a hybrid PV/wind microgrid established in Laguna Grande, Peru. The microgrid plant was built based on community surveys about energy utilization, social-economic elements, and factors like predicted growth and available funding. The project was built in a collaborative manner, with the community being involved at various stages. Even though the hybrid energy system was effective in supplying electricity to the site, monitoring data revealed a 10% loss of load due to peak demand, technical issues, and occasional low solar and wind resources. A techno-economic study of stand-alone hybrid PV-wind turbine-diesel-battery energy system was undertaken using HOMER software simulation for various locations in Tamil Nadu, India, based on analysis of various system combinations [21]. The findings revealed that the PV-wind-diesel-battery configuration is the most cost-effective for all sites [21]. Jain and Sawle [22] studied the economic analysis of standalone and grid-connected hybrid renewable energy systems for a remote location in India. The authors found that PV/wind/microhydro/battery/converter/DG is the most reliable and cost-effective solution for off-grid scenarios. Solar PV, fuel cells, biogas, and microhydro hybrid energy systems are all sustainable and contribute to socio-economic growth [22]. Moghaddam, Bigdeli, and Moradlou [23] presented a design for a stand-alone PV/WT/battery system for Zanjan, Iran, with the main goal of minimizing the total cost of the hybrid system while considering reliability constraints such as generation and load uncertainties. Methods such as the improved crow search algorithm for optimal sizing were used. Simulation results were presented in deterministic and probabilistic formats, and load demand was calculated using Monte Carlo simulation. They concluded that a probabilistic approach of the hybrid system designing is necessary to know the accurate cost and reliability. An off-grid renewable energy hybrid system with different battery technologies including lead acid, lithium-ion, and nickel-iron for rural electrification in India was optimized using the MATLAB environment, and Salp Swarm algorithm was used to find an optimal configuration from configurations [24]. The results show that the nickel-iron battery-based renewable energy hybrid system offers the lowest levelized cost of energy when compared to other batteries for the configured system [24]. A study of hybrid energy systems for a rural location in Nigeria revealed that using a combination of locally available abundant energy resources reduces greenhouse gas emissions and improves power reliability [5]. A study of the techno-economic optimal configuration of a small PV-wind hybrid energy system with both battery and pumped hydro storage systems modeled for a remote island (Deokjeokdo Island, South Korea) [25]. HOMER Pro was employed for running simulation while considering actual electricity consumption data for a year and noting that energy storage accounts for a significant portion of cost in setting up renewable energy systems. The analysis showed that pumped hydro storage system is the most cost-effective storage system [25].

Hybrid energy system installation in rural areas is influenced by investment expenses, operation and maintenance costs, reliability, optimal configuration, and security [26, 27]. Combining renewable energy sources in hybrid systems optimally improves system reliability and efficiency while enhancing hybrid system economics and reduces greenhouse gas emissions [28]. Major power quality difficulties in hybrid energy systems, such as voltage and frequency fluctuation, and harmonics, can be addressed to a large extent with proper design, improved fast response control capabilities, and hybrid system optimization [29]. [30] Set up an event-triggered distributed hybrid control scheme to achieve secure and cost-effective operation of the integrated energy system. The outputs of the energy hubs are controlled using a containment and consensus algorithm, and according to the outputs, the power of the electricity and heat loads can be accurately shared without knowledge of the network parameters. Additionally, the results show a decrease in communication cost based on the event-triggered communication technique used to create the associated protocols. [31] presented a deep reinforcement learning-based data-driven optimal control strategy for a virtual synchronous generator to achieve control performance goals for frequency regulation and active power regulation. Simulation results confirm the viability and efficacy of the proposed method. The results of an optimal energy management and techno-economic analysis of a stand-alone hybrid PV/wind/DG/battery microgrid for a remote area in Tamil Nadu, India, using HOMER software, show that the PV/battery combination is the most cost-effective configuration and that in comparison with a traditional isolated distribution system with DG, it also results in a 68 percent reduction in emissions [32]. A reduced-order aggregate model based on balanced truncation approach has been developed as a preprocessing technique for the real-time modeling of large converters with inhomogeneous beginning conditions in DC microgrid. The results demonstrate a reduction in input-output mappings error, and the simulation outcomes demonstrate the precision of the suggested approach [33]. [34] Conducted research on a method for accurate current sharing and voltage regulation in hybrid wind/solar systems. The research used distributed adaptive dynamic programming to find the best control variable and achieve accurate current sharing/voltage regulation, and the results showed that the model met the predetermined goals.

The study's major goal is to assess energy demands, renewable technology acceptability, and obstacles faced by previous energy systems in a rural area, and then design an energy system to match those demands while also considering the system's economic and technical benefits. This work also explores the viability of electrifying the village with a highly renewable energy-based hybrid system and the relevance of doing so for minimizing locals' contribution to deforestation, enhancing system reliability, and lowering fuel costs.

In the assessment, a survey was conducted from September 07, 2020, to September 11, 2020. During the survey 98 household, 6 commercial enterprise, 2 community leaders, and 1 farmer were interviewed.

2. Location Description

Jamataka is a rural low-income village located in the central region of Botswana about 45 km west of the city of Francistown. Low standards of living characterize the village, a high unemployment rate with many people depending on government subsidies as a means of livelihood with an estimated income of a household of around 50 US Dollars ($) per month. The village has a population of about 1320 people.

2.1. Energy Technologies in Use in Jamataka Village. Figures 1 and 2 show the common energy technologies used by households and businesses in Jamataka. These energy technologies have drawbacks such as being unreliable and emitting CO2, for example, the generators. In addition, the available technologies are costly to maintain and operate. For instance, the generators need to be fueled and repaired when they break down.

Figure 1 shows an example of solar systems for lighting and charging purposes commonly used by Jamataka households. The solar lighting systems comprise a small-sized solar panel with a torch and radio. Alternatively, some systems use solar panels to charge old car batteries, which are then used to charge mobile phones. However, there seems to be a general lack of knowledge and capacity on the installation of solar home systems. The common practice observed from the community is that appliances are often directly connected to solar panels. In addition, there were reports of some appliances (phones and batteries) exploding and junction boxes of solar panels burnt due to lack of voltage regulators in the installations. Most Solar Home Systems (SHS) are small and used for charging radios, mobile phones, torches, and lights.

Typical small generators shown in Figure 2 are used only during special occasions like Christmas holidays and weddings. Most of the generators are owned by households with commercial activities like tailoring, tuck shops, and welding. Business enterprises also use Liquid Petroleum Gas (LPG) and direct current refrigerators.

2.2. Energy Consumption in the Village. In terms of energy use, the majority of Jamataka households use petrol or diesel generators to power their activities (sewing and welding), while others use firewood and SHS. However, over half of the respondents interviewed indicated that the capacity of the current SHS does not meet their demand. The use of petrol or diesel fuel for running generators was reported as the most expensive energy source, with most businesses spending between $17 and $26 per month. Figure 3 shows the results of the interviews, which demonstrated a substantial level of dissatisfaction with generator capacity.

Figure 4 shows the willingness survey results on switching to electricity. Willingness and ability to switch to electricity survey indicated that over 83% of households interviewed were willing to switch to electricity if available. In Figure 4, 97.8% of the household interviewed indicated that they would switch to electricity for lighting purposes. It is clear that lighting energy has the highest need in the village. Mobile phone charging was another energy need why respondents

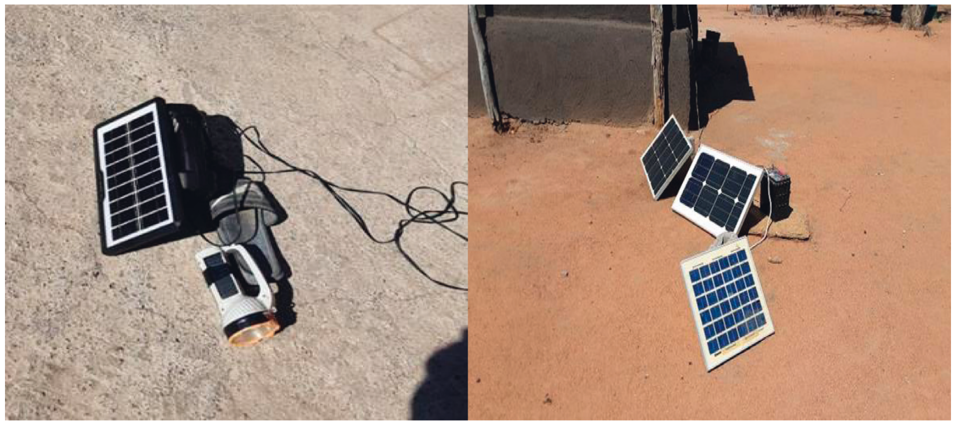


Figure 1: Solar systems in households in Jamataka.

Figure 2: Generators used by households in Jamataka.

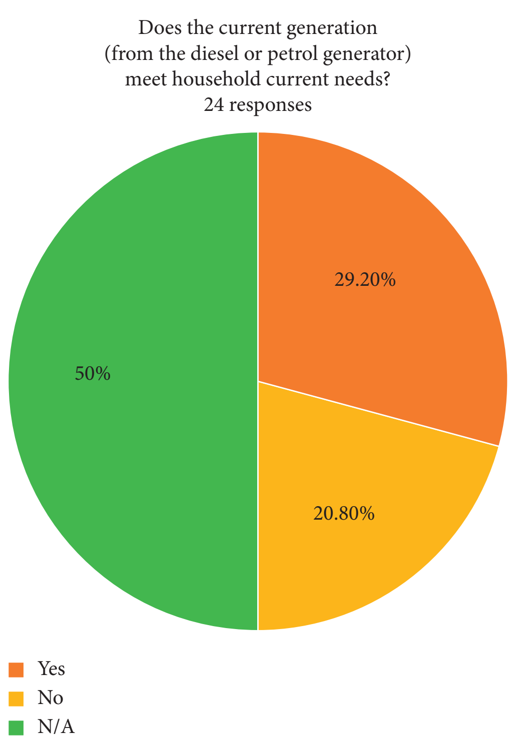


Figure 3: Diesel or petrol generators and households' current needs survey results.

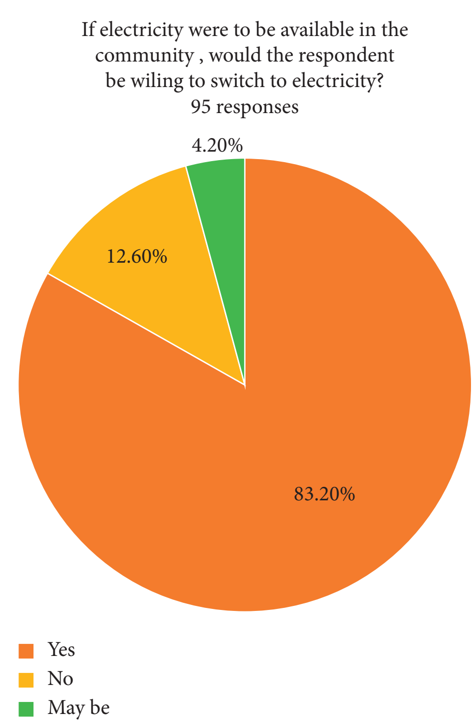


Figure 4: Willingness to switch to electricity.

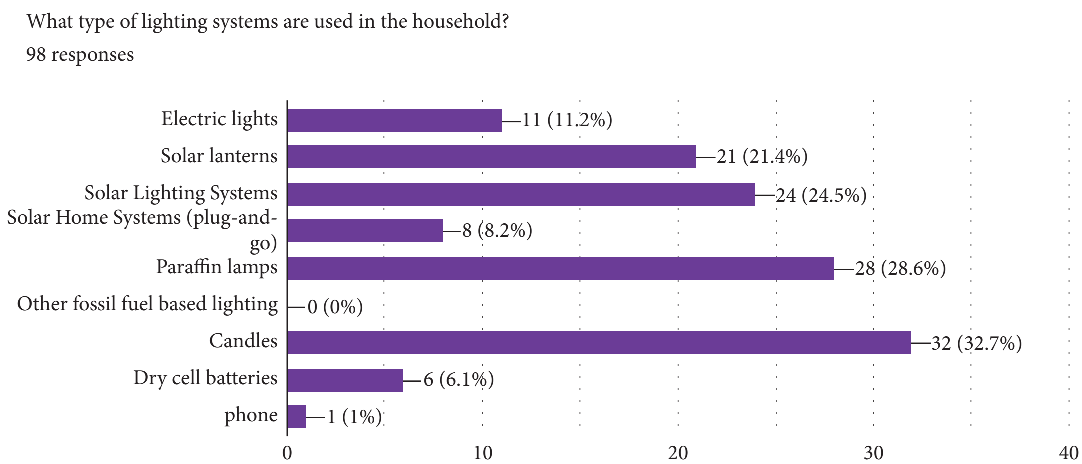


Figure 5: Lighting systems used in the village.

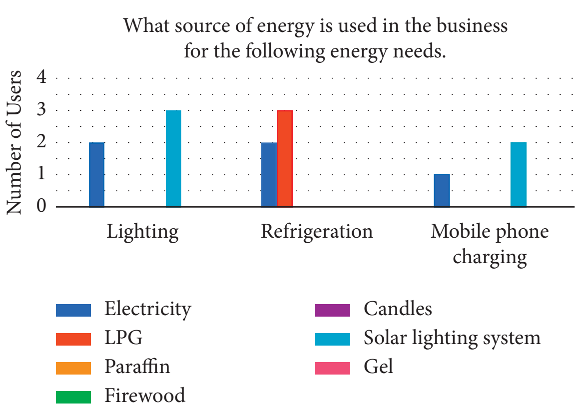


Figure 6: The village business energy sources.

wanted to switch to electricity, followed by entertainment, cooking, then refrigeration, in that order. Various reasons were cited for willingness to switch including convenience, security, and self-development achievement. Most respondents preferred a prepayment method for electricity consumption (75.3%), while 11.8% were indifferent to a post- or prepayment method.

Most households indicated that they preferred firewood for cooking because it was inexpensive and was easily available. This suggests that they are not likely to switch to an energy source for cooking where they will have to pay for it. The majority of households use open fire cooking, and stoves are very minimal.

Figure 5 shows that 32.7% of households use candles for lighting, followed by paraffin lamps with 29%. More than half of the respondents (i.e., 54%) preferred use of solar energy for lighting in one form or the other (solar lanterns, solar lighting systems, and solar plug and go), which is convenient, and they did not need to carry it around. The biggest challenge households had with solar systems was that they do not work when the weather is cloudy and most had to supplement with paraffin lamps or candles when their solar systems do not work. There were also cases of systems not lasting for the required number of hours.

There were six business enterprises identified in the village and these included minigroceries shops (termed tuckshops), tailoring, and one liquor shop. 50% of the enterprises own generators with an average of 2000 W shown in Figure 6.

3. Load Calculation

3.1. Estimated Electrical Load for the Village. The estimated electrical load is based on an assessment of the power consumption of households in the village.

Table 1 shows the electrical weekday load calculation for the year, with daily demand higher in the afternoon hours because of use of appliances like ceiling fans.

Figures 7 and 8 depict the village's weekly load profile for the year and the monthly average load profile, respectively. The average electricity usage is roughly 165.29 kWh/day, and the scaled peak primary load demand is 27.31 kW. The total load is 1165.58 kWh/d.

3.2. Location Resources. The meteorological data obtained from NASA resource website via the HOMER software, such as solar resource, wind resource, and temperature, are used in the modeling section of this study.

Figure 9 depicts the village's monthly average global solar radiation. The months of September to December and January to February have higher solar irradiance levels than other months. On a monthly basis, solar radiation is 5.8 kWh/m^2/day. Data on solar radiation were collected over a 22-year period between 1983 and 2005.

Figure 10 shows that the monthly average wind speeds for the village are usually above 6 m/s in July to November and January to April, indicating that wind turbines could be used for various applications (e.g., water pumping, agro-processing, and power generation) during these months. The month with the highest wind speed of 7.47 m/s is October. The average wind speed is 6.43 meters per second. Even the lowest speeds are greater than 5 m/s, which is the minimum requirement for wind power applications. It is pertinent to mention that the village has a wind regime that is higher than the national average resource and would be a good location

Table 1: Load demand calculation for Jamataka.

S. no.	Category	Appliance	Power rating of appliances (W)	Number of appliances	Operating hours	AC load (kWh/d)
1	Households	Television	150	40	3	18
		Decoder	14	40	3	1.68
		Irons	1500	30	2	90
		Radios	100	70	3	21
		Washing machine	1300	10	2	26
		Hair dryers	1000	20	1	20
		Hair clippers	15	50	2	1.5
		Electric stoves	1200	30	6	216
		Electric kettles	1500	40	2	120
		Fridges	250	25	24	150
		Food blenders	250	70	5	87.5
		Electrical sewing machine	50	15	6	4.5
		Electrical welding machine	250	10	1	2.5
		Laptops	60	20	10	12
		Mobile phones	5	320	11	17.6
		Light bulbs	20	600	5	60
2	School	Printer	50	2	1	0.1
		Fan	90	10	3	2.7
		Fridge	250	1	5	1.25
		Desktop computer	100	3	8	2.4
		Lamps	20	40	12	9.6
4	Businesses	Fan	90	15	3	4.05
		Fridge	250	5	24	30
		Lamps	20	20	6	2.4
		Printer	50	3	9	1.35
		Speaker	2000	6	12	144
		TV	150	6	3	2.7
5	Churches	Fan	90	20	3	5.4
		Lamps	20	20	12	4.8
		Speaker	2000	5	3	30
6	Health post	TV	150	1	9	1.35
		Fan	90	10	4	3.6
		Fridge	250	1	24	6
		Desktop computer	100	2	16	3.2
		Lamps	20	20	12	4.8
		Printer	50	2	4	0.4
		Microscope	100	2	6	1.2
7	Police post	Desktop computer	100	2	8	1.6
		Lamps	20	15	12	3.6
		Fan	90	5	4	1.8
Total load (kWh/d)						**1116.58**

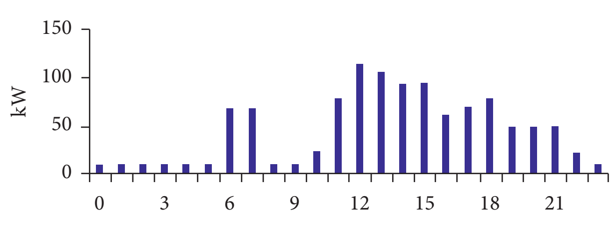


Figure 7: Weekday load profile of the village on an hourly basis during the year.

for different aero turbines applications. The wind data were gathered between 1984 and 2013.

Figure 11 shows that the average monthly temperatures vary from 15.35°C to 25.86°C. The yearly average temperature is 22.9°C, with the highest temperature recorded in November.

4. Methodology

This section discusses components setups, mathematical modeling, costing, replacement, and operations and maintenance expenses. The components are a solar photovoltaic system, a wind turbine system, a diesel generator, a battery system, and a converter.

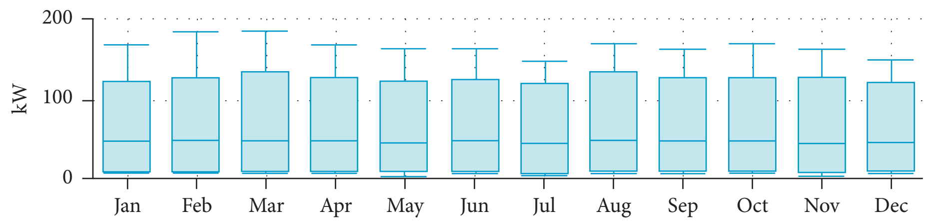


Figure 8: Monthly average load profile of the house.

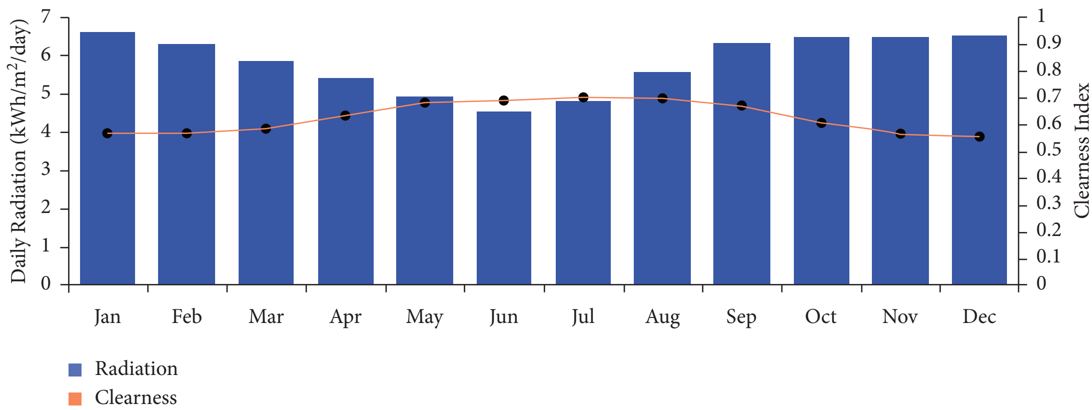


Figure 9: Monthly average global radiation at Jamataka.

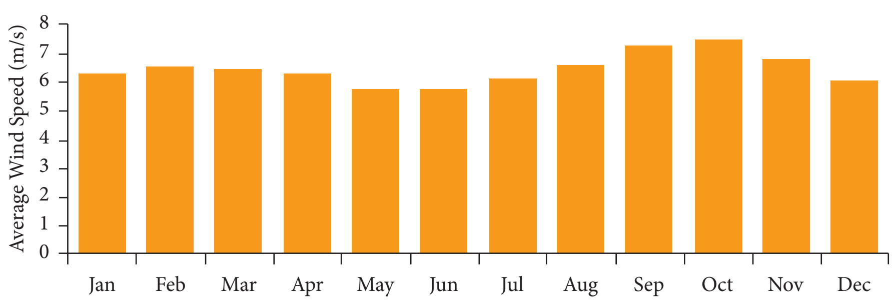


Figure 10: Average monthly wind speed of Jamataka.

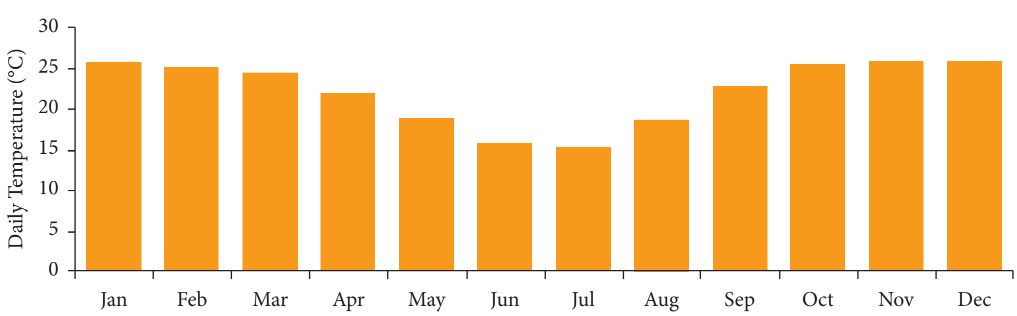


Figure 11: The monthly average temperature of Jamataka.

The system was optimized with the aid of the HOMER Pro software. HOMER Pro was created by the National Renewable Energy Laboratory in the United States and is largely used for the design of distributed generation systems via modeling, optimization, and sensitivity analysis techniques.

The system is designed so that its load may be met by a hybrid system that combines a PV and wind energy source, with a diesel generator added to the mix to address intermittent power supply problems. However, the results analysis will choose the configuration that offers the

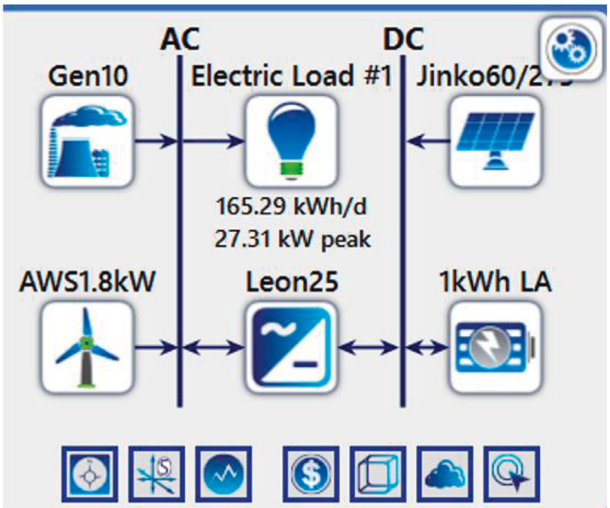


FIGURE 12: General optimized hybrid system architecture.

optimal balance of economic and technical benefits. The energy from solar PV and wind is stored in a battery bank through the bidirectional converter and charge controller. The output from the solar PV and wind is used to power the AC load considered in this study by converting the DC energy from the solar and battery to AC energy using an inverter.

Figure 12 depicts the proposed AC/DC hybrid system configuration.

4.1. Photovoltaic System. The PV module used in the simulation is a 60-polycrystalline cell module with an efficiency of 16.8% and a derating factor of 88 percent. Jinko Solar manufactured the module with a 275 Watts rated capacity and an operating temperature and temperature coefficient of 45°C and -0.4°C, respectively. The initial capital and replacement costs were set at $472.73 per kW and $436.36 per kW, respectively, and the annual operation and maintenance cost was assumed as 10% of the initial capital cost for this PV. The PV module has a 25-year life span.

The PV system's total power output is modeled as [35]

$$P^t_{pv} = N_{pv} \times P_{pv}(t), \tag{1}$$

where P^t_{pv} denotes total PV output power, N_{pv} represents the number of PV panels, and $P_{pv}(t)$ stands for the hourly power produced from the PV system.

4.2. Wind System. Each wind turbine is rated at 1.8 kW, with a capital cost of $6000 and a replacement cost of $5600. The average cost of operating and maintaining a wind turbine is assumed as $120 per year. This wind turbine has three blades and a hub height of 12 m, with a survival speed of 50 m/s. During the wind turbine modeling process, ambient temperature effects were considered.

The power produced by the wind depends on wind speed and the cross-sectional area it sweeps through [36]

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

where P represents the wind power and it is measured in Watts, ρ symbolizes the air density measured in kg/m^3, A stands for the cross-sectional area, which the wind sweeps through, V denotes the wind speed in m/s, and C_p defines the power coefficient of the wind generator.

4.3. Diesel Generator. In renewable energy hybrid systems, generators maintain consistent power for peak loads. For this investigation, a generic 10 kW fixed capacity generator was chosen. The capital cost is $4,800 per generator, while the replacement cost is $4,600 per generator. The cost of operation and maintenance is $0.01 per hour. The price of fuel (diesel) in 2022 in Botswana is about $1.08 per liter [37]. The lifetime of diesel generator (DG) is 15,000 operating hours with a minimum load factor of 25%.

The majority of the costs associated with running generators are due to fuel; hence, the fuel consumption rate is modeled as [38]

$$FC = \sum_{DG}\left(a + bP_{DG} + cP_{DG}^2\right), \tag{3}$$

where FC denotes the fuel consumption rate; a, b, and c represent the diesel generator cost coefficient; and P_{DG} defines the generator power capacity.

4.4. Battery System. Batteries are utilized in renewable hybrid power systems to store extra energy that can be utilized when the system needs it. The battery's life is determined by how many times it is charged and discharged each day. The battery model used in this study is a generic 1 kWh lead-acid battery. An individual battery rating's nominal voltage, maximum capacity, and nominal capacity are 12 V, 83.4 h, and 1 kWh, respectively. Each battery's initial and replacement costs are set at $550 and $500, respectively.

The performance of a battery system is determined by its state of charge (SOC), which is expressed as [38]

$$SOC(t) = SOC(0) + \beta c \sum_i P_c^B(i, t) - \beta d \sum_j P_d^B(j, t), \tag{4}$$

where P_c^B and P_d^B represent power capacity for charging and discharging of the battery at time t, and βc and βd represent the charging and discharging efficiency of the battery, respectively.

The battery system must function within the permitted SOC limits established by each manufacturer as expressed by

$$SOC_{\min} \le SOC(t) \le SOC_{\max}. \tag{5}$$

The battery system performs at its optimum when depth of discharge (DOD) is taken into account.

$$SOC_{\min} = 1 - DOD. \tag{6}$$

4.5. Converter. Converting AC to DC and vice versa uses converters that consist of inverters and rectifiers. The

Table 2: Optimization results of the proposed system under different setups.

Item (units)	System setups			
	PV/WT/DG/battery	PV/WT/battery	WT/DG/battery	PV/DG/battery
Economic performance				
NPC ($)	343181.3	339804.26	392603.98	404537.61
LCOE ($)	0.2857	0.298	0.3404	0.3365
Technical performance				
Renewable fraction (%)	72.2	100	50	65.9
PV production (kWh/yr)	37083	65814	0	84667
WT production (kWh/yr)	41336	56838	51671	0
DG production (kWh/yr)	16771	0	28952	20592
Excess electricity (kWh/yr)	33655	62111	22204	41982
Unmet electric load (kWh/yr)	56.5	3124	2457	0.0539
Capacity shortage (kWh/yr)	332	6057	5608	11.4
Batteries nominal capacity (kWh)	31	50	7.01	56
Batteries lifetime throughput (kWh/yr)	23344	40000	5600	44800
Batteries expected life (yr)	10	4.43	3.4	7.74
Batteries autonomy (hr)	2.7	4.36	0.61	4.88
Maximum inverter output (kW)	10.4	14.9	1.67	18.5
Maximum rectifier output (kW)	6.71	11.2	1.33	1.27
Emissions produced				
Carbon dioxide (kg/yr)	16653	0	28249	19485
Carbon monoxide (kg/yr)	126	0	214	147
Unburned hydrocarbons (kg/yr)	4.59	0	7.79	5.37
Particulate matter (kg/yr)	7.64	0	13	8.94
Sulfur dioxide (kg/yr)	40.9	0	69.3	47.8
Nitrogen oxides (kg/yr)	143	0	243	168

converter utilized in this study has a 10-year life span and a 96 percent inverter and 94 percent rectifier efficiency. The initial capital cost is $ 550 per kW, whereas the replacement cost is $ 500 per kW. For each converter, an annual O&M cost of $ 120 is considered.

Figure 12 depicts the general hybrid system that includes a DG, renewable energy sources, a converter, and a battery system.

5. Results and Discussion

This section contains the results and discussion of the hybrid system employed to supply the electrical power demand of Jamataka. The performance of the system in terms of technical, economic, and environmental factors was investigated using four distinct configurations. This study assumed a project's lifetime of 25 years. A benchmark interest rate of 3.75% was adopted from Trading Economics [39]. This value corresponds to Botswana's discount rate recorded from October 2021 to February 2022. Botswana's inflation rate for 2020 is 1.89 percent [40].

5.1. Optimization Results. HOMER tool optimizes hybrid system component sizes in the simulation to match the load demand of the case study site. As a result, all system combinations were evaluated in terms of NPC, COE, and technical performance indicators. The optimal solution was chosen based on the lowest value of NPC and environmental impact of each system from optimization results of every base case. Table 2 presents the four distinct setups that were considered for analysis.

The results indicate PV/WT/battery combination as the most viable option in terms of NPC and emissions. However, the LCOE of PV/wind WT/DG/battery combination has the lowest value followed by that of PV/wind WT/battery combination. The most viable hybrid system configuration consists of PV, WT, converter, and battery rated at 35.4 kW, 19.8 kW, 26.1 kW, and 50 units, respectively. This combination is the most sustainable energy system with a renewable fraction of 100%, 0% electricity supply from nonrenewable sources, and zero or low levels of emissions.

In general, all combinations have minor reliability issues of less than 6% because they have low unmet loads. The PV/WT/battery combination has the highest unmet load of about 3124 kWh/year, which is 5.8% of the total load. The PV/DG/battery combination, on the other hand, is the most reliable, with the lowest unmet load (0.0539 kWh/yr), which is 0.02% of the total load. The PV/DG/battery combination has the lowest reliability rank due to power intermittency since the energy sources that make up the combination include solar resource. Solar energy can only be harnessed during the day, but wind energy can mostly be harnessed at night. The diesel generator reduces the problem of intermittency in the other combinations.

The yearly battery throughputs and the battery lifespan have an inverse relationship. From the optimization exercise, the PV/WT/DG/battery combination has the lowest battery throughputs, estimated at 23344 kWh/year, resulting in the longest service lifespan, projected at 10 years. The WT/DG/battery combination, on the other hand, has the highest

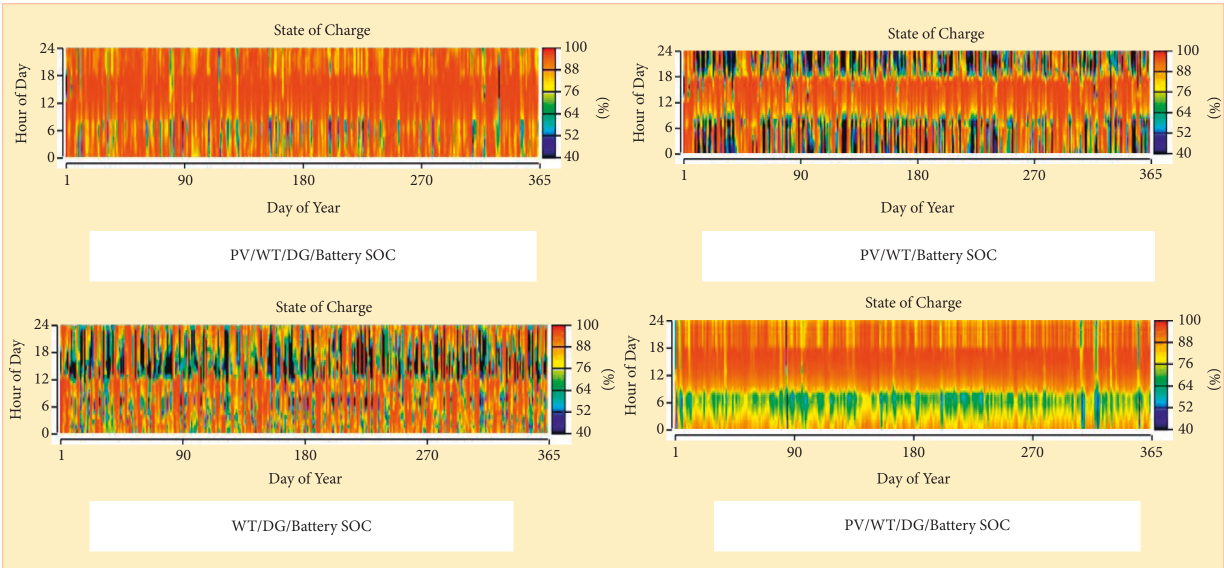
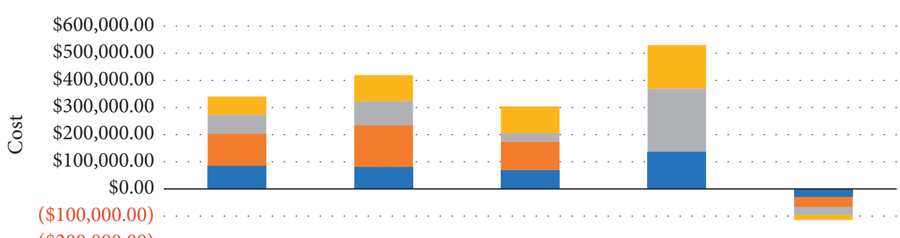


Figure 13: The battery system state of charge for the different combinations.



	Capital ($)	Replacement ($)	O & M ($)	Fuel ($)	Salvage ($)
PV/DG/Battery	$67,305.54	$96,076.53	$98,911.21	$160,531.04	($18,286.71)
WT/DG/Battery	$69,567.05	$88,977.41	$30,349.53	$232,739.64	($29,029.65)
PV/WT/Battery	$118,472.58	$153,280.92	$105,398.04	$0.00	($37,347.27)
PV/WT/DG/Battery	$84,985.61	$80,933.01	$69,544.99	$137,197.85	($29,480.16)

Axis Title

■ PV/WT/DG/Battery ■ WT/DG/Battery
■ PV/WT/Battery ■ PV/DG/Battery

Figure 14: Cost summary of system setups.

throughputs, estimated at 5600 kWh each year, resulting in the lowest battery lifespan of 3.4 years.

PV/DG/battery combination has the highest average battery autonomy hours of 4.88 hours, followed by PV/WT/battery, PV/WT/DG/battery, and WT/battery combinations with 4.36 hours, 2.7 hours, and 0.61 hours, respectively.

Table 2 also shows that the PV/DG/battery combination has the largest inverter output of 18.5 kW, owing to the highest PV capacity, which charges the batteries, as opposed to the WT/DG/battery combination, which has the lowest output of 1.67 kW. In terms of rectifier output, the PV/WT/DG/battery combo has the maximum rectifier output of 6.71 kW.

The battery state of charge (SOC) is normally defined as the ratio of the available capacity and the maximum possible charge that can be stored in a battery. It can be measured as an hour of the day, day of the year, or month of the year. In Figure 13, SOC is measured in hour of day with an initial value of 40%.

The cost summary for the five configurations is shown in Figure 14. The lowest capital cost, which is $67305.54, is for the PV/DG/battery combination, which is 3.25%, 20.8%, and 43.19% less than the capital costs for PV/WT/battery, PV/WT/DG/battery, and PV/WT/battery setups, respectively.

Wind turbine, battery system, converter, and battery replacement costs account for main system replacement costs; however, PV has no replacement costs because the project duration is 25 years, corresponding to the PV lifespan.

Fuel costs are not necessary in the PV/WT/battery configuration, but they are $ 232739.64 for the WT/DG/battery system, which is 31.03% and 41.05% more than PV/DG/battery and PV/WT/DG/battery, respectively.

The basic load suppliers in the optimum system are photovoltaic and wind turbines. When there is excess power left over after meeting the load demand, the solar panels and wind turbines also charge the battery bank. When there is insufficient or no power coming from the solar panels and wind turbines, the battery bank discharges to feed the load. This optimization considers load following, a hybrid energy dispatch technique in the HOMER Pro, because it frequently proves to be the best option in systems with a mix of renewable energy, especially when the renewable power output occasionally surpasses the load.

6. Conclusion

Hybrid energy system for a rural location in Botswana is designed, taking into account the site's renewable energy resources. HOMER Pro software is used for optimal sizing of components and to run simulations. Based on the results of the simulations, the following is determined:

(i) The most optimal model (PV/wind/battery system) employs 100% renewable energy, resulting in zero carbon emissions. Solar generates 53.7% of production, while wind generates 46.3%. The system has a 25-year lifespan with a 7.6% return on investment and an 11.4% internal rate of return. Due to high initial investments in renewable energy and rural people's minimum earnings, government subsidies and favorable policies could help speed the development of renewable energy projects in Botswana's rural villages, lowering the LCOE.

(ii) The site's adequate local renewable energy resources suit the adoption of renewable energy hybrid systems that are more reliable and effective.

By implementing this proposed system, the community will be able to lessen the deforestation caused by their reliance on firewood, as well as the health issues caused smoke because of using firewood. Furthermore, by augmenting current power sources in the village, the proposed system will contribute to the economic development of the community as households will have access to power for economic activities such as welding and hair salons, among others. Consequently, this will improve the standard of living for the people of Jamataka village. In the long run, educational attainment levels are likely to increase as pupils get access to learning technologies such as computers and Internet. In addition, learners are likely to have more time to study as they have access to lighting during the evening, thereby extending their study time.

The capacity of the battery system must be carefully considered when designing standalone renewable energy systems but must also take into account the costs associated with their operation and maintenance. As a result, optimizing the system is the best course of action.

Researchers, investors, and government energy departments can use this study as a guide as they choose hybrid energy systems for nearby villages and villages with wind and solar data that are very comparable to the one in this study.

Data Availability

Data will be provided on request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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