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Cost-Effective Design of a Hybrid Solar PV-Genset Power Supply System for a Small Rural Community (Zuro-kpumi) using HOMER

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Abstract:- One of the main challenges with Ghana's energy sector is the supply of power to remote areas of the country. Most of the rural communities in Ghana, including Zuro-kpumi, a remote area located in Yendi, in the Northern part of Ghana, is off the grid due to financial constraints on the side of the government, the terrain and the economic status of such communities to afford electricity. This study tries to analyse the feasibility of a cost-effective hybrid solar PV-Genset power system for Zuro-kpumi, a small rural village, in the Northern part of Ghana. The hybrid solar PV system consists of Canadian Solar All-Black CS6K-290MS PV, ABB PS-BatP3 Li-Ion battery, a generic 10 kW diesel generator and a generic system converter. The hybrid system lifetime is about 25 years. There is a projected cost reduction in electricity generated by solar PV in the next decade; making the overall cost of the hybrid PV-Genset system cheaper. Using a load profile, HOMER software and sensitivity analysis, this study was able to analyse various feasible systems from which the most cost-effective system was chosen. The most feasible, cost-effective system was found to be the PV-diesel-generator with a battery system. This study was able to determine the most feasible and cost-effective system for Zuro-kpumi.

Keywords:- *Clearness Index, Cost-Effective, HOMER Software, Hybrid PV-Genset, Optimization, Sensitivity Analysis.*

I. INTRODUCTION

The electricity generation mix in Ghana has mainly been from hydro and thermal sources, with the country taking steps to introduce significant amounts of renewable electricity to diversify the mix. At the end of 2016, the generation mix stood at approximately 57.21 per cent of thermal against 42.79 per cent of hydro sources. Renewable generation sources haven't played any major role in the generation mix, contributing only 0.2 per cent to the generation mix in 2016. The Energy Commission of Ghana reports a total of 500 kW of installed solar PV systems (both grids connected and with battery backup) owned by individuals and institutions [1]. Ghana, located geographically around the equatorial sun-belt gives her a great advantage for her to exploit the abundant solar energy resources. May is the month with the highest solar irradiation (5.897 kWh/m^2-day), August recorded the lowest measurement (4.937kWh/m^2-day) in Wa; the capital of the Upper West region, which has the highest level of solar irradiation (5.524 kWh/m^2-day) across the country [2].

The cost for extending grid electrification may reach as high as US$ 8,000 – US$ 12,000 (GBP 4,935 – GBP 7,402) per household and US$ 19,070/km (GBP 11,763/km) for remote areas [3, 4]. The diesel generator, although relatively cheaper in investment cost and much easier to install, raises several concerns, especially on the environmental impact caused by the CO_2 emission, fuel chain supply, and potential of fuel spillage during transportation and operation[5]. Many countries around the world, such as India, South Africa, and Australia are currently doing extensive research and development of hybrid power systems for rural communities that comprise stand-alone generators integrated with renewable energy sources or micro-grid based power systems with distributed renewable energy resources. The PV hybrid genset system comprises of a photovoltaic system which harnesses solar power, a converter, battery system and a diesel generator. The PV hybrid genset system has a lifetime of 25 years. Integrating the diesel generator with photovoltaic arrays, the so-called PV-Diesel Hybrid System has several advantages such as reducing daily operation hour of diesel generator while servicing to the clients increase and the diesel engine is always running on its best efficiencies [6]. Integration of renewable energy sources, in particular solar PV and wind turbines, with diesel generation can significantly reduce diesel fuel use and maintenance costs, thereby reducing Greenhouse Gas emissions [7]. The cost of solar PV has declined rapidly in recent years as increasing sales has supported large-scale low-cost manufacture of PV panels and research into producing more efficient and cheaper PV panels. Though a hybrid PV/Genset system with a battery backup would be more stable, the effects of not using a battery backup in terms of the cost and how the system would behave in such a rural community with a very low load demand have not been addressed. The purpose of this paper is to determine the most feasible cost-effective system while still considering the consequences of not having a battery backup in such a small community. This study was conducted in May of 2020.

II. MATERIALS AND METHODOLOGY

Defining the project's geographical location and the number of customers to be served was the basic and initial step we took before designing our mini-grid system. We needed to know the available resources, taking into account its availability, cost, quantity and quality. Sizing of our system, after finding a suitable location, was the next step, and this required the use of standardized tools and techniques, of which we made use of HOMER.

A. Location and Background Information

Zuro-kpumi is the selected area for this study. It is situated in the Northern Region of Ghana specifically the Mion District. The coordinates are 9º26.2’ north and 0º33.0’ west. Zuro-kpumi is a farming community that has a population of about five hundred (500) residents. This rural community has no electricity. Due to the lack of electricity, the residents depend on kerosene lamps and candles for their lighting purposes. There are about sixty-three (63) households in Zuro-kpumi. Due to the geographical location of Zuro-kpumi, solar is the best renewable energy resource for the design of a mini-grid. PV power systems convert energy from sunlight into electricity.

B. The Solar energy potential of Zuro-kpumi

According to the NASA website (www.nasa.gov), the daily solar radiation range of Zuro-kpumi is 5.5 kWh/m^2/day to 6 kWh/m^2/day. From the table below the maximum value of radiation is achieved in September and the minimum value in December. The clearness index can also be obtained: The clearness index is an index which helps measure the clearness of the atmosphere. According to the data, the clearness index is highest in January (dry season) and lowest (rainy season) in May. The value ranges from 0.519 to 0.612.

Table 1: Monthly Average Solar Global Horizontal Irradiance(GHI) of Zuro-kpumi.

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.612	5.480
February	0.606	5.840
March	0.566	5.810
April	0.542	5.700
May	0.519	5.390
June	0.538	5.500
July	0.535	5.490
August	0.534	5.550
September	0.570	5.850
October	0.579	5.640
November	0.596	5.400
December	0.609	5.300

C. The Price of Diesel in Ghana

It is a hybrid PV Genset system. It is important to know the cost involved in running the diesel generator. As of 18th May 2020, a litre of diesel cost $ 0.752. The price of the diesel may increase if the cost of transportation is added and it depends also on the international market.

D. Simulation Software

The simulation software used for this study is the HOMER. There are several other software available for renewable energy analysis, but HOMER was chosen due to its popularity and ease of use. It defines the component specifications and also estimates different types of costs, including the life cycle costs, the operation, and maintenance cost, the per year operating cost, and as well as the cost of energy. The system consists of PV, battery, diesel generator and inverter. HOMER can be used to determine the best feasible system which can meet the load most economically. Our study focused on determining the initial cost, replacement cost, operating cost, the Total Net Present Cost (TNPC) and the (COE).

E. System Description

Electrical Load Profile

According to Joy News online, the population of Zuro-kpumi is about five hundred (500) and an average of eight (8) per household. Hence Zuro-kpumi has a total of sixty-three (63) households. The method of obtaining the load profile was taken from an international journal of renewable energy research titled ‘Feasibility Analysis of Standalone PV/Wind/Battery Hybrid Energy System for Rural Bangladesh’. To create the load profile, the loads considered for each household were 1 television set, 1 fan, 3 fluorescent bulbs, 1 radio, and 1 cellular phone. The load calculation is shown below. To generate a realistic load profile the probabilistic method is used [8]. The probabilistic approach for load profile modelling is based on fitting a probability distribution to load power values at each time instance resulting from a set of load profiles. The load profile of Zuro-kpumi is also shown below.The peak loads are mainly in the afternoon and evening. The peak load is 17.3 kW. The annual average load is 249.00 kWh/day.

Table 2: Various Loads and Ratings

Appliance	No. of Units	Unit(W)	Power(Wh)	Average Consumption (kWh/day)
TV	63	70	4,410	52.32
Fan	63	50	3,150	40.24
Bulb	189	40	7,560	139.32
Radio	63	30	1,890	14.08
Phone	63	5	315	3.04

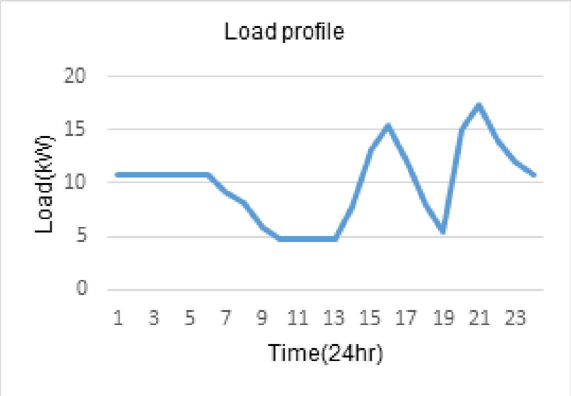

Fig. 1. The load variation for a 24 hour period.

F. Components

HOMER requires various inputs to run. This study focuses on a cost-effective system thus relatively cheaper and efficient components were selected. The following components where used.

i . PV

The PV considered is the Canadian Solar All-Black CS6K-290MS. The PV panel has a lifetime of 25 years and a de-rating factor of 88%.

The ground reflectance is considered at 20% and the temperature effect is also considered. The nominal operating temperature is 45ºC and the temperature coefficient is -0.390%/ºC.

ii. Battery

The ABB PS-BatP3 Li-Ion battery was considered in making the battery bank. This lithium-ion battery was chosen due to its increased efficiency, relatively low cost, and long lifespan. This ABB PS-BatP3 Li-Ion battery is 3.7 V with 0.289 kWh of energy storage. Its nominal capacity is 78 Ah. The lifetime is 10 years for each battery, but this may vary depending on the number of times they are charged. The lifetime throughput is 1,732.00 kWh for each battery. The roundtrip efficiency is 95%. The initial State of Charge is 10% and the minimum State of Charge is 10%.

iii. Diesel generator

The generic 10 kW fixed capacity generator is considered. The generator operating lifetime is 15,000 hours and the minimum load ratio is 25%. The efficiency of the output power curve is shown below.

iv. Converter

The lifetime of the converter is 15 years. The efficiency of the inverter and rectifier is 95% and 90% respectively. The relative conversion ratio of AC and DC is taken to be 100%.

The table of the cost of the various components is shown below.

Table 3: Cost parameters of the components

Component	Capital Cost	Replacement Cost	O&M Cost
PV	$184.85/kW	$184.85/kW	$425.38/yr
Battery	$17.09/pc	$17.09/pc	0
Diesel Generator	$85.47/kW	$85.47/kW	$0.66/hr
Converter	$512.92/kW	$100.66/kW	0

G. Hybrid System Modelling

The modelling of the system includes defining the decision variables and the size range of the components. Project lifetime is 25 years since the largest component of the system expires within that time.

To obtain an optimum system, the following parameters need to be defined:

- The size range of PV, battery, converter, and diesel generator.

H. Strategy of Operation

The strategy of operation can be summarized by the following:

- During normal operation, the PV being a renewable source of energy will serve the load. When the generation by the PV exceeds the load demand the battery gets charged.
- During the peak period, the PV cannot meet the load demand, the generator starts and supplies the necessary power. During the generator operation, the battery is not charged by the power of the generator. The load following approach is used. The load following strategy is a dispatch strategy whereby whenever a generator operates, it produces only enough power to meet the primary load.

III. RESULTS AND DISCUSSIONS

The simulation was conducted without using a battery backup and using a battery backup.

A. Without battery backup

The HOMER software suggested two systems. The first suggestion was a combination of the PV and the diesel generator and the other one being just the diesel generator. The PV/diesel generator system has a more cost-effective system.

The PV/diesel generator combination had the following cost.

Table 4: PV and diesel generator costs.

Cost	Genset	PV
Capital	$1,709.40	$20,228.95
Replacement	$9,567.94	$0.00
O&M	$9,055.89	$10,876.52
Fuel	$216,417.61	$0.00
Salvage	$252.52	$0.00
Total	$236,498.31	$31,105.47

The total cost of this PV/diesel generator is $267,603.78 A warning was attached to this setup saying: this system has a renewable penetration, high enough to cause stability problems that require more detailed modelling. Adding some form of storage, such as a flywheel or battery bank may help.

Table 5: Diesel generator system costs.

Cost	Genset	System
Capital	$1,709.40	$1,709.40
Replacement	$12,401.15	$12,401.15
O&M	$11,614.88	$11,614.88
Fuel	$293,091.97	$293,091.97
Salvage	$163.8	$163.8
Total	$318,653.59	$318,653.59

Relatively the PV/diesel generator is more cost-effective than the diesel generator system. That has a system cost of $267,603.78.

B. With battery backup

The HOMER suggested two systems with different configurations, from which the PV/diesel generator/battery system was the more cost-effective system considering its capital cost, operating cost, the Total Net Present Cost (TNPC) and the Cost of Energy (COE). The next cost-effective system is the PV/battery system. The table below shows the optimized results of the hybrid systems.

Table 6: Optimization Results of the two hybrid systems.

Cost ($)	PV	Battery	Converter
Capital	69,720.01	12512.82	2,002.37
Replacement	0.00	1,105.43	849.55
O&M	37,486.41	3,396.95	0.00
Fuel	0.00	0.00	0.00
Salvage	0.00	149.88	159.89

The table below summarizes TNPC of the PV/diesel generator/battery system.

Table 7: The Net Present Cost

Component	PV/diesel generator/battery system	PV/battery system
PV (kW)	107	377
Battery (pc)	1,342	732
Converter (kW)	25.7	39.0
Diesel Generator (kW)	10	-
Initial Capital Cost ($)	44,894.36	84,235.21
Operating Cost ($/yr)	1,593.16	3,289.74
Fuel Cost($/yr)	128.72	-
TNPC($)	65,490.43	126,763.76
COE($/kWh)	0.06	0.11

The total cost of the PV/diesel generator/battery system is $65,490.47.The lifetime of this system is about 25 years. HOMER estimates the possible emission of the exhaust gas (CO_2) to be 454 kg/yr emitted by the diesel generator.

PV/Battery system does not have any diesel generator; there is no fuel cost, fuel transportation problem, and exhaust gas emission. The lifetime of this system is about 25 years. The PV produces 100% of the electricity since it is the only source of energy. The table below summarizes TNPC Cost of the PV/battery system.

Table 8: The Net Present Cost of the PV/battery system

Cost ($)	PV	Battery	Converter	Generator
Capital	19,779.02	22,940.17	1,320.50	854.70
Replacement	0.00	2,026.62	560.25	0.00
O&M	10,634.60	6,227.75	0.00	45.08
Fuel	0.00	0.00	0.00	1,663.54
Salvage	0.00	274.77	105.45	181.72

C. Sensitivity Analysis

Sensitivity analysis is mainly performed to observe what happens when changes occur on certain factors and their effect on the system. The factors that may change include solar radiation, fuel price, load demand, and inflation. The yearly solar radiation changes for Zuro-kpumi has been considered. Hence there is no need to perform sensitivity analysis for solar radiation. From the optimization results, the

PV/diesel generator/battery system is the most optimum one. Therefore, fuel price sensitivity is performed. Also, the effect of load change and change of the inflation rate is performed. The sensitivity analysis was done by varying one parameter at a time while keeping the others constant.

i. A rise in the net present cost when the fuel price is increased.

Sensitivity analysis has been performed to demonstrate the effect of change in fuel price on the system. Fuel prices are largely due to favourable international market prices. There are many reasons diesel prices rise. When demand is greater than supply, the decline of the Ghana Cedi, when traders think diesel prices will be higher; they bid even higher, are some of the causes for this increase. A 30% increase is likely for a period of four months. The fuel price was increased from $0.74/L to $ 0.96/L as a 30% increase. It is observed that the operating cost increased from $1,593.16 to $1,631.79, the net present cost increased from $65,490.43 to $66,052.99 and the Cost of Energy increased from $0.06 to $0.078. HOMER estimated the possible emission of the exhaust gas (CO_2) to be 454 kg/yr. With the increase in fuel prices by 30%, the PV/diesel generator/battery system was still found to be the optimum system.

ii. A rise in the total present cost and CO_2 emissions when the load is increased.

Sensitivity analysis was performed on the system to demonstrate the effect of load change. The annual average load was increased by 40% from 249 kWh/d to 348.6 kWh/d. With the increase in load, the total present cost had increased by 44.30 % and COE had increased by only 3.07 %. The operating cost had increased by 53.87% and HOMER estimated the possible emission of the exhaust gas (CO_2) had increased from 454 kg/yr to 1,162 kg/yr.

iii. A rise in operating cost when the inflation rate is increased.

The inflation rate varies based on the economy of a country. Since the lifetime of PV/diesel generator/battery system is estimated to be 25 years, and the inflation rate can vary from time to time, therefore it would be important to observe the effect of change in the inflation rate. For the previous simulations, the inflation rate was set at 2%. The new inflation rate was set at 4% and 6%. At 4% inflation, the net present cost had a 6% increase, the operating cost had a 0.01% increase. At a 6% inflation rate, the net present cost had a 15% increase and the operating cost had a 0.27% reduction.

With the increase in the inflation rate, the PV/diesel generator/battery system was still the most optimum configuration.

D. Discussion

This study, conducted a cost-effective analysis of a hybrid power system. The study considered a system with a battery backup and one without one. Between the two considerations, it was noted that the system without a battery backup was extremely expensive compared to one with a battery backup. There were two optimization results of the system with the battery backup from the HOMER simulation. PV/diesel generator/battery system and the PV/battery system were the suggested configurations. Of these two, the PV/diesel generator/battery system was more cost-effective. This result is congruent with other studies results, where the PV/diesel generator/battery system was the most optimum and cost-effective system [9, 10, 11, and 12].

The PV/Diesel generator/Battery system has a relatively low cost compared to the PV/Battery system but the only downside of the PV/Diesel generator/Battery system is that it causes CO_2 pollution due to the presence of the diesel generator [13]. HOMER estimated the possible emission of the exhaust gas (CO_2) to be 454 kg/yr.

The load following strategy was used; Under the LF strategy, a generator produces only enough power to satisfy the load demand and does not charge the batteries [14].

IV. CONCLUSION

The optimum configuration for the Zuro-kpumi is the PV/Diesel generator/Battery system. The load was developed based on a regular rural lifestyle. The main parameters of analysis are per unit energy cost, initial cost, per year operating cost, and total net present cost of the system. This system is a reliable and cost-effective energy source with a total cost of $65,490.47 which is the lowest of all the feasible configurations. The best configuration without a battery backup has a system overall cost of $267,603.78. This system without the battery backup has stability issues and a form of storage is necessary for efficient running as well as reducing the cost of the system.

The sensitivity analysis carried out showed that the system can handle an increase of 40% in load. The sensitivity analysis also shows the effect of change in inflation rate and fuel rate on the system, it showed an increase in all the cost parameters.

V. FUTURE SCOPE

The next step of this study is to apply the aforementioned methods on larger communities and how these methods could help reduce the cost of electricity for its residents.

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Conflict of Interest:

There is no conflict of interest in this work.

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