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Optimal Design of Renewable Hybrid Energy System for a Village in Ghana

Emmanuel Obuobi Kwame Addo
Email: hodaddo79@yahoo.com

Dr. Johnson Asumadu
Email: johnson.asumadu@wmich.edu

Dr. Philip Yaw Okyere
Email: okyerepy@yahoo.com

***Abstract* – This paper proposes a methodology for configuring hybrid solar-wind-diesel-energy systems at minimum cost and minimum dumped load. An iterative optimisation technique has been developed to calculate, the optimum system configuration to achieve minimum hours of loss of power supply and minimum annualized cost of system (ACS). The decision variables included in the optimization process are the number of PV modules, wind turbines, batteries and diesel generators. The proposed method has been applied to the analysis of a hybrid system which supplies power to a cluster of villages in Bonsaaso located in the Amansie- West District of the Ashanti Region of Ghana. The optimal configuration consisted of 92 PV panels, 9 wind turbines, 32 batteries and 1 diesel generator. The optimal configuration obtained is capable of providing maximum reliability of the system and minimum load rejection over a 20 year period of the project.**

***Keywords* – Iterative Optimization Technique Configuring, Renewable Energy, Solar Energy, Wind Energy, Hybrid Energy**

I. INTRODUCTION

Electric power is one of the ingredients for rural development and therefore a major solution to rural-urban migration. Unfortunately, some villages in Ghana have not been connected to the national grid because the villages are far away from the national grid and therefore it is costly to provide them with electricity from the conventional electrical power generating sources. Solar and wind renewable energy sources have been found to be two of the best options for the supply of electric power to villages [1]. The effect of weather and climate changes on the wind and PV energy systems may be overcome by combining energy storage systems such as battery back-up. However, the design of such system will require an optimisation technique in order to guarantee a full economic use at lowest investment and cost of hybrid system

Various optimization techniques have been proposed by researchers for the design of both single and hybrid systems. Graphical construction techniques for obtaining the optimum combination of wind turbine, battery and PV array in a hybrid solar–wind system has been presented in [2] .For example, a house was used as a typical hybrid load .This may not work for a village characterized by varying load demand and complexity of the system. In the graphical methods, only two parameters (either PV and battery, or PV and wind turbine) are included in the optimization process. In [3] iterative optimization techniques have been proposed based on minimum hours of the loss of power supply model for a hybrid solar–wind system.

This methodology can find the global optimum configuration of the system with relative computational simplicity, but the configurations are sometimes not cost effective. In [4] - [8] a probabilistic approach is presented. This is based on convolution technique to incorporate the fluctuating nature of the load resources. This eliminated the need for time-series data for assessing the long-term performance of a hybrid solar–wind system for both stand-alone and grid-connected applications. In [9] - [10] a heuristic technique is proposed .This is based on evolutionary algorithms for optimizing the size of a PV and wind integrated hybrid energy system with battery storage.

A common disadvantage of the optimization methods described above is that their minimization of the system cost consists of employing probability programming techniques or linearly changing the values of corresponding decision variables causing increased computational effort requirements.

Furthermore, the monthly average data used in these approaches do not produce reliable or accurate results. In addition, these methodologies normally do not take into account some system design characteristics, such as PV modules slope angle and wind turbine installation height, which also highly affect the resulting energy production and system installation costs.

In this paper, one optimal sizing model for a stand-alone hybrid solar–wind –diesel system employing battery banks was developed based on minimum dumped load (MDL) and annualized cost of the system (ACS) concepts. The optimization procedure aims at finding the configuration that yields the best compromise between the two considered objectives: MDL and ACS. The decision variables included in the optimization process are the number of PV modules, wind turbine, batteries and a given size of a diesel generator. The configurations of a hybrid system that can meet the system power reliability requirements with minimum cost can be obtained by iterative technique.

The technique lists the number of best configurations with their costs and degree of dumped loads. The configuration with the lowest overall cost and least dumped load was selected as the best configuration of the hybrid system. The method offered a minimum

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computational time. The data on wind speed and irradiance recorded by the meteorological department in Ashanti Region Ghana for every hour of the day for a given period were used. These data were used to calculate the average power generated by a wind turbine and PV module for every hour of a typical day in a month. The load at Bonsaaso was used as the load demand of the hybrid system.

II. MODELLING OF THE HYBRID OF SYSTEM

A. Photovoltaic

The output power of PV panel is influenced by the sun insolation. Using the solar radiation available on the tilted surface the hourly, power output of the PV panel at any time *t* can be calculated from the following equation:

$$P_{PV-ARRAY}(t) = \eta .\, A_{PV} \,.N_{PV}\,.Ins(t) \qquad (1)$$

where N_{PV} is the total number of PV panels, η is Power conversion efficiency of a PV panel (%) A_{PV} is Area of a single PV panel (m^2), $Ins(t)$ is sun insolation data (W/m^2).

B. Wind turbine

The appropriate output of wind turbine depends on the wind speed at the location, air density, swept area of rotor and the efficiency associated with the energy conversion from mechanical energy to electrical energy. Wind turbine curves are sometimes used to determine wind turbine power output. The electrical power generated at any time, *t* $P_{WT}(t)$ is given by:

$$P_{WT}(t) = \begin{cases} 0 & \upsilon_c \le \upsilon(t) \\ \frac{1}{2}\rho.A.\upsilon^3(t).\eta_w \eta_c N_{WT} & \upsilon_c \le \upsilon(t) \le \upsilon_r \\ P_{Rated}.N_{WT} & \upsilon_r \le \upsilon(t) \le \upsilon_f \\ 0 & \upsilon(t) > \upsilon_f \end{cases} \qquad (2)$$

where ρ_{wind} is density of air (1.22 kg/ m^3), A is area swept by the wind blade in m^2

η_{WT} is wind turbine efficiency; η_C is efficiency of convertor; $\nu(t)$ is wind speed in m/s;

$\nu(c)$ is wind speed in m/s; $\nu(t)$ is wind speed in m/s; $\nu(r)$ is rated wind speed in m/s ; $\nu(f)$ is furling wind speed in m/s ; N_{WT} is the number of wind turbines ; P_{rated} is the rated power of wind turbine in Kw

C. Diesel generator

The nominal voltage of a diesel generator in most cases matches the AC bus or DC bus nominal voltage. Several diesel generators can run in parallel to meet the load demand. The determination of operational cost of the diesel generators is given in [12]. The fuel cost (FC) of a diesel generator at any time is given by

$$FC = C_f \sum_{t=1}^{8760} F(t) \qquad (3)$$

and the hourly fuel consumption $(F(t)$ of a diesel generator is given as

$$F(t) = 0.246 \times P_{DG}(t) + 0.08415 \times P_R \qquad (4)$$

Where $P_{DG}(t)$ *is* Power generated by the diesel generators (kW), P_{Rated}*is* the rated power of the diesel generators (kW) , and C_f *is* Fuel cost per litre (US$/l).

From the above equations the rated power and power generated by diesel generator influence its fuel consumption. Therefore, diesel generators should not be operated under its minimum output power. On the other hand maximum efficiency of diesel generator corresponds to their rated power. Diesel generators, therefore, have to operate between the rated power and specific minimum output power:

$$P_{\min} \le P_{DG} \le P_{Rated} \qquad (5)$$

D. Battery

The total power $(P_G(t)$ generated by PV arrays, wind turbines or diesel generators at any time can be expressed as

$$P_G(t) = P_{PV}(t) + P_{WT}(t) + P_{DG}(t) \qquad (6)$$

Power from batteries are required whenever the generated power from renewable sources or diesel generators are not able to meet the load demand. On the other hand, power is stored in the batteries whenever the generation from the renewables or diesel generators exceeds the load demand. At any time the state of charge of the battery (*SOC*) is related to the previous state of charge, energy production**,** and consumption of the system from *t-1* to *t*. Two cases are considered n determining the energy stored in the battery at any given time *t*.

1. During the charging process if the total output of the wind turbine and PV array or Diesel generators exceed the load,
2. During the charging process if the total output of the wind turbine and PV array or Diesel generators exceed the load, the available battery capacity at time t can be expressed as follows:

$$SOC(t) = SOC(t-1) + P_G(t) - P_L(t) \qquad (7)$$

3. When the load demand is greater than available generated power, the battery will be discharged to cover the deficit .Therefore the available battery capacity at time t can be expressed as

$$SOC(t) = SOC(t-1) - (P_G(t) - P_L(t)) \qquad (8)$$

The value of $SOC(t)$ cannot be less than the minimum state of charge, $SOC_{\min}$. Also during charging process, the value of $SOC(t)$ cannot be higher than the maximum state of charge, $SOC_{\max}$, where $SOC_{\max}$ is 1 and

$SOC_{\min}$ is determined by depth of state of charge (DOD).

$$SOC_{\min} = 1-(DOD)\,. \tag{9}$$

For example in the simulation, a DOD value of 0.8(80%) was used. Therefore, from (9) the $SOC_{\min}$ is 0.2 (20%)The constraints on the batteries is given by

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{10}$$

E. Load

The power supply from wind-PV hybrid system or the diesel generators is determined by the load demand.The data used for the determination of number of components in the hybrid system are as shown in table1.The peak load are in the evening.

III. ECONOMIC MODEL OF THE HYBRID SYSTEM

There are many ways to calculate the economic viability of a distribution generation and energy efficiency projects. The capital and replacement costs, the operation and maintenance costs must be combined in some manner so that a comparison may be made with the costs of not doing the project. In this project, because a diesel generator is considered in the hybrid system, fuel cost is featured prominently in the cost analysis. The economic calculation is based on Annualised Cost of the System (ACS) so that the best benchmark in the system cost analysis can be found.

The ACS of the system is composed of annual capital cost (ACC), annual replacement cost (ARC), annual fuel cost of diesel generators (AFC), and annual operation and maintenance cost (AOC). The components whose annual costs are considered include PV panels, wind turbines, diesel generators and batteries. The annual cost of the system (ACS) can be calculated as

$$ACS = ACC + ARC + AOC + AFC \tag{11}$$

A. Annual Capital Cost

The annual capital cost of each component (ACC_i) that does not require replacement during the project life time can be calculated as

$$ACC_i = C_{cap_i} \times CFR(k, Y_{project}) \tag{12}$$

$$ACC = (N_{PV} C_{cap_{PV}} + N_{WT} C_{capWT} + N_{DG} C_{cap_{DG}} + N_{BAT} C_{capBAT}) \times CFC(k, Y_{project}) \tag{13}$$

where N_{PV} is the number of batteries, N_{WT} is the number of wind turbines,where N_{DG} is the number of diesel generators, C_{CapPV} is the capital costs of PV panel , C_{CapDG} is the capital costs of a diesel generator, C_{CapBAT} is the capital costs of a battery, $Y_{project}$ is project life time (20 years), and *CFR* is capital recovery factor, a ratio to calculate the present value of each annual cash flows.

CFR is given as

$$CFR(k, Y_{project}) = \frac{k(k+1)^{Y_{project}}}{(1+k)^{Y_{project}} - 1} = \frac{0.1327(1.1327)^{20}}{(1.1327)^{20} - 1}$$

$$= 0.145 \tag{14}$$

where*k* =13.27 % is annual real interest rate consisting of nominal interest rate and annual inflation rate.

k can be calculated as

$$k = \frac{k' - f}{(1+f)} = \frac{0.28 - 0.13}{1 + 0.13} = 0.1327 \tag{15}$$

where *k*`=28% is rate at which a loan can obtained and *f* =13% is annual percentage inflation rate

B. Annual replacement Cost

System. The annual replacement cost is the annual cost value for replacing units during project life time. The units that need replacement is batteries and other units will work until the project life time. The annual replacement cost can be calculated as

$$ARC_i = C_{rep} \times SFF(k, Y_{rep})$$

$$= \left(\frac{Y_{project-}Y_{BAT}}{Y_{BAT}}\right) \times N_{BAT} C_{Cap,BAT} (SFF(k, Y_{project}) \tag{16}$$

Where, C_{rep} is the replacement costs of individual components of battery and wind turbine, Y_{rep} is the lifetime of each component type in number of years , N_{WT} is the number of wind turbines, N_{BAT} is the number of batteries , Y_{BAT} is the lifetime of batteries, which is 5 years, and *SFF is* sinking fund factor (a ratio to calculate future value of series equal annual cash flow)

SFF is calculated as

$$SFF(k, Y_{rep}) = \frac{k}{(1+k)^{Yrep} - 1} = \frac{0.1327}{(1.1327)^{20}} = 0.012 \tag{17}$$

C. Operation and Maintenance Cost

The annual operation and maintenance costs, AOC_i , of each component in the hybrid system after n years is given as

$$AOC_i = M_i (1+f)^n \tag{18}$$

where M_i the annual operation and maintenance cost of each components in the hybrid system, n is in years – useful life time of the project (20 years).

The total annual operation and maintenance costs, AOC_{TOTAL} of the components in the hybrid

$$AOC_{TOTAL} = \sum_{i=1}^{N} AOC_i (1+f)^n =$$

$$N_{PV} \sum_{j=1}^{20} M_{PV} (1+f)^n + N_{WG} \sum_{j=1}^{20} M_{WG} (1+f)^n +$$

$$N_{BAT} \sum_{J=1}^{20} M_{BAT} (1+f)^n + N_{DG} \sum_{j=1}^{20} M_{DG} (1+f)^n$$

(19)

D. Annual fuel Cost of Diesel generators

Annual fuel cost of a diesel generator is calculated as

$$AFC_i = TFC \times CFC(k, Y_{project}) \qquad (20)$$

where *TFC* is total fuel consumption for 20 years.

E. The objective function

Using equations (13, 18, 20 and 21) the objective function can be written as

$$f(x) = \begin{matrix}[N_{PV} C_{cap_{PV}} + N_{DG} C_{cap_{DG}} + N_{WT} C_{capWT} + \\ N_{BAT} C_{capBAT}] \times CFC(k, Y_{project})\end{matrix}$$

$$N_{PV} \sum_{j=1}^{20} M_{PV} (1+f)^n + N_{WG} \sum_{j=1}^{20} M_{WG} (1+f)^n + \\ + \\ N_{BAT} \sum_{J=1}^{20} M_{BAT} (1+f)^n + N_{DG} \sum_{J=1}^{20} M_{DG} (1+f)^n$$

$$\left(\frac{Y_{project-} Y_{BAT}}{Y_{BAT}} \right) \times N_{BAT} C_{cap,BAT} (SFF(k, Y_{project}) +$$

$$N_{DG} \sum_{j=1}^{20} FC \times CFC(k, Y_{project}) \qquad (21)$$

IV. OPERATION OF HYBRID WIND, PV, DIESEL, AND BATTERY SYSTEM

A. Analysis of the hybrid system.

Inputs of the hybrid system will comprise PV generators and Wind generators. Based on the number of the PV array N_{PV} and the number of wind turbine N_{WT}, the power generated $(P_G(t)$ by wind turbine and PV generator at any time t is calculated as:

$$P_G(t) = P_{PV} + P_{WT}(t) \qquad (22)$$

During the system operation at any time interval, one of the following three situations can appear:

1. $P_G(t)$ can be greater than the load demand $P_L(t)$. In this situation, based on the number of batteries, N_{BAT},the power surplus is stored in the batteries as $P_{BAT\ CH}(t)$. The maximum power that can be stored in the battery is $P_{BATcharmax}(t)$. If $P_G(t)$ is greater than $P_{BATcharmax}(t)$ the excess power, $P_{EX}(t)$, is dumped.

If the load demand is greater than what the PV and wind turbine can supply, the excess power may come from the batteries, provided the state of charge of the batteries is above the minimum charge and power .However, if the state of charge of the batteries is at minimum, the diesel generator will be turned on to meet addition load and charge the battery

Using the values of capital costs, replacement cost, maintenance cost and life span from table 1 for a PV panel, from table 2 for wind turbine, from table III for battery and from table 4 for a diesel generator, equation (21) becomes

$$f(x) = [(411 \times 0.145 + 6.64(1+0.13)^{20})x_1 + \\ (2197.02 \times 0.145 + 15.1975(1+0.13)^{20} x_2 + \\ (205.02 \times 0.145 + 4.42(1+0.13)^{20} + \\ 3 \times 205.02 \times 0.012)x_3 + (11873.85 \times 0.145)] + B \qquad (23)$$

where B is the cost of fuel due to the use of diesel generator and it can be obtained from the simulation results.

Table I: The hourly temperature, sun irradiance, wind speed and load demand of the village.

Time(hour)	Temperature(^oC)	Irradiance(w/m^2)	**Load(kW)**	**Wind(m/s)**
1	20.5	300	10.5	4.0
2	20.5	300	10.0	3.5
3	21.0	300	10.5	4.0
4	22.5	300	14.0	3.0
5	24.0	300	15.0	3.2
6	24.5	300	16.0	4.3
7	26.0	400	15.0	5.0
8	28.0	400	14.0	4.3
9	28.5	400	13.0	3.7
10	30.0	500	10.5	4.7
11	31.0	600	11.5	5.0
12	31.5	800	14.0	4.5
13	30.5	700	14.5	3.2
14	30.0	500	15.0	4.7
15	29.5	400	16.0	4.8
16	28.0	400	17.0	3.5
17	27.5	400	18.0	4.5
18	28.0	400	19.5	3.0
19	24.0	350	20.0	3.5
20	24.0	325	18.5	4.5

21	22.5	300	17.0	3.5
22	22.0	250	13.0	3.3
23	22.0	200	10.5	3.0
24	20.0	200	10.0	2.8

B. Technical data and unit cost of the components of Hybrid system

Table II: Technical data and unit cost of the PV panel in the Hybrid system

Component	Rating/w	Capital cost/$	Replacement cost/$	Maintenance cost	Area/m^2	Life time/ years	Efficiency %
PV panel	120W	411	411	6.64	1.07	20	16

Table III: Technical data and unit cost of the Wind turbine in the Hybrid system

Components	Rating/kW	Capital cost/$	Replacement cost/$	Maintenance cost	Life time/ years	Rated velocity/m /s	Cut-off Velocity m/s	Furling Velocity/ m/s
Wind turbine	10	2197.02	2197.02	15.97	20	5	2	10

Table IV: Technical data and unit cost of the battery in the Hybrid system

Component	Rating/Ah	Capital cost/$	Replacement cost/$	Maintenance cost	Voltage /V	DOD %	Efficiency %
Battery	120	205.17	205.17	4.42	12	80	85

Table V: Technical data and cost of the diesel generator in the Hybrid system

Component	Rating/kW	Capital cost/$	Replacement cost/$	Maintenance cost/$	Fuel coefficient	Life time/ years	Cost /litre/$
Diesel Gen	20	11873.85	11873.85	4.8	A=0.246 B=0.841	20	1.05

V. RESULT AND DISCUSSION

Table VI: Results of the optimal configuration of the Hybrid System

N_{PV}	N_{WT}	N_{BAT}	N_{DG}	ACC	ARC	AFC	ACS	DUMPED
96	7	32	1	4521.06	2427	22675.47	29624.47	1.79
92	10	40	1	4834.41	2812	22301.07	29948.39	17.15
92	10	36	1	4804.17	2777.27	22031.76	29613.20	17.15
92	10	32	1	4773.93	2741.63	21762.45	29278.01	17.15
92	9	36	1	4697.62	2654.74	22557.51	29909.87	12.46
92	9	32	1	4667.38	2619.11	21064.48	28350.96	5.91

Table VII: The hourly generation of each of the components in the hybrid system.

Time/hr	PV Array	Wind turbines	Batteries	Load demand	Total generation	Dumped power
1.00	3.15	0.54	11.52	10.30	10.35	
2.00	6.30	1.81	6.25	13.20	13.38	
3.00	6.30	4.28	11.52	14.50	14.98	
4.00	9.45	8.37	11.52	15.00	17.82	1.98
5.00	9.45	1.81	3.00	19.60	19.78	
6.00	11.03	0.54	2.40	12.10	12.15	
7.00	12.60	4.28	3.86	15.00	15.43	
8.00	7.88	8.37	9.26	10.00	10.84	
9.00	7.88	8.37	11.52	9.80	13.99	3.35
10.00	11.03	1,81	11.52	12.50	12.83	0.15
11.00	6.30	4.28	7.68	14.00	14.43	
12.00	12.60	8.37	8.20	13.70	13.88	
13.00	6.30	0.54	5.26	13.10	15.53	

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14.00	9.45	4.28	10.74	11.50	12.34	
15.00	9.45	0.54	8.77	11.90	11.95	
16.00	11.03	4.28	11.52	11.70	12.56	0.43
17.00	9.45	0.54	6.45	15.00	15.05	
18.00	14.18	1.81	2.65	19.60	19.78	
19.00	4.73	1.81	11.52	19.80	19.98	
20.00	12.60	0.54	4.80	19.80	19.85	
21.00	9.45	1.81	11.52	19.40	19.59	
22.00	6.30	4.28	3.08	18.60	19.03	
23.00	12.60	0.54	11.52	17.90	17.95	
24.00	7.80	8.37	7.43	19.50	20.34	

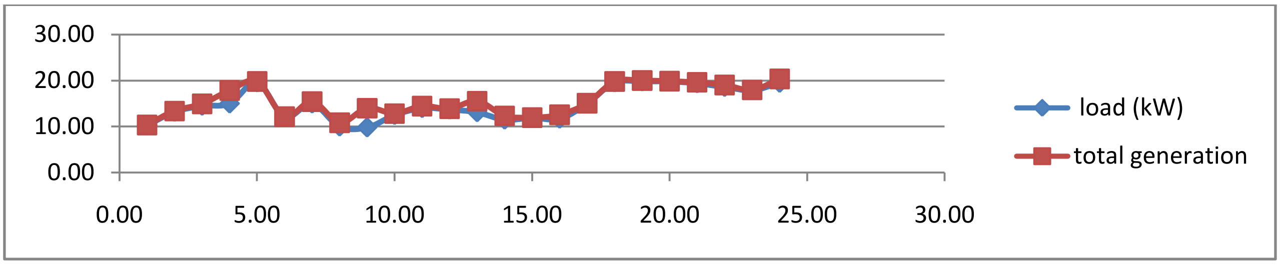

Fig.1. A graph of daily load demand and the total generation from the hybrid system against time in hours

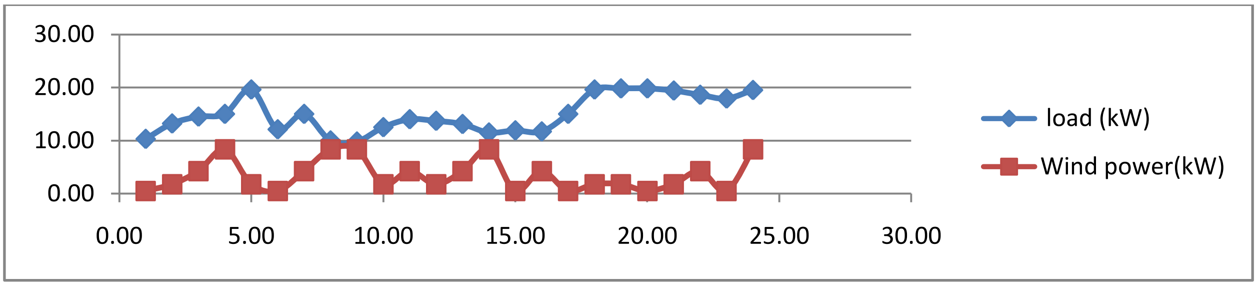

Fig.2. A graph of daily load demand and the total generation wind power against time in hours.

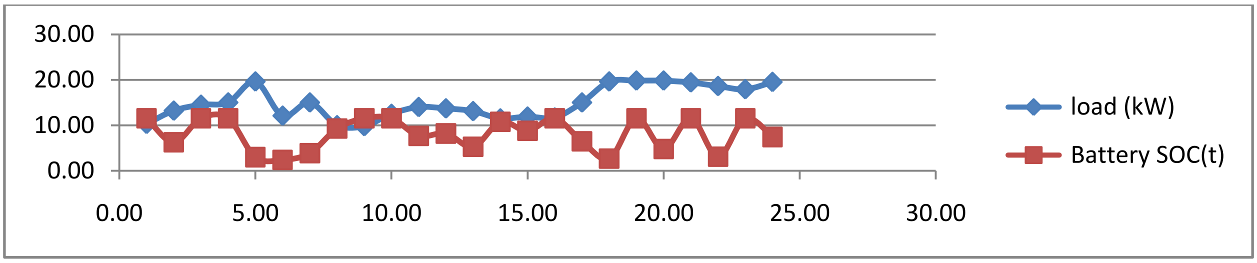

Fig.3. A graph of daily load demand and the battery SOC against time in hour

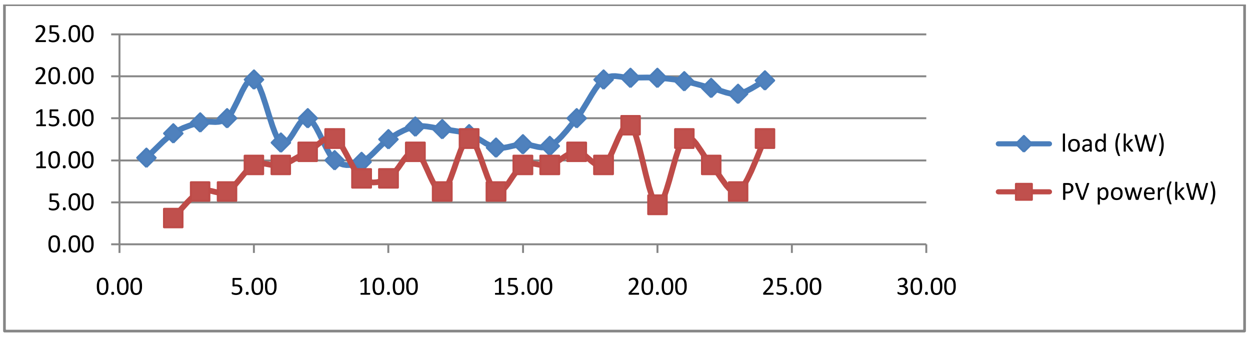

Fig.4. A graph of daily load demand and the battery SOC against time in hour

An optimum configuration has been attained from the iterative method. Metrological data of wind and solar irradiance, load profile**,** and other data were obtained for the cluster of villages in Bonsaaso in Ghana. The load profile is represented as a power sequence and considered as constant over time step. The iteration is done for data duration of one hour time for 24 hours and projected into a year

The project life-time in this paper is 20 years. Batteries are replaced three times during the project life-time. The inflation rate of 13% and interest rate of 28% based on actual economic condition in Ghana are used in the iteration. The fuel price for diesel generators is $1.05 per litre. In the iteration, the optimal configuration was found to consist of 92 PV panels, 9 wind turbines, 32 batteries**,** and 1 diesel generator.

The optimal configuration is capable of supplying the load demand at any hour in every day in a year with a zero load rejection and minimum dumped power as shown in Fig. 1. The overall capital cost of the hybrid system is $28,350.96 and consists of $21,064.48 for fuel consumption, $4,667.38 for capital cost, and $2,619.11 for maintenance cost.

VI. CONCLUSION

In this paper, an iterative algorithm was used to determine the optimal number of generating units of wind-turbine generator (WT), photovoltaic array (PV), batteries(BAT)**,** and diesel generators(DG)for a stand-alone hybrid power system. The iterative method was used for the design of a power supply system to a cluster of villages at Bonsaaso. It was shown in fig.1 that the obtained optimal configuration of the hybrid wind-PV-battery system could reliably overcome the effect of the climatic change on the supply of electricity to the load.

The simulations results prove that the best solution to reliable load supply without interruption under climatic changes is the combination of a diesel generator with the hybrid wind-PV-battery system. The optimal number and type of each system component is calculated such that the 20-year round total system cost is minimized subject to the constraint that the load power requirements are completely covered at a minimum dumbed load. The 20-year round total system cost is equal to the sum of the respective components capital and maintenance costs. The results achieved show that the hybrid PV wind battery diesel power system can be considered as the optimum combination system. A detailed analysis of the different types of cost (capital cost, installation cost, annualized operation and maintenance have been put in table VI. The contribution of each generating source to cover the daily load demand are as shown in fig.2 to fig. 4

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