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Design of a PV/Wind Hybrid Power Generation System for Ayitepa Community in Ghana

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Abstract: The provision of universal access to electricity is the ultimate aim of many governments worldwide. This goal is however not easily attained, especially in Sub-Saharan African countries and across many developing nations due to the lack of capital, sufficient generation capacity to meet growing loads, aged or dilapidated transmission and distribution infrastructure, high supply costs, coupled with the weak financial position of utilities and their inability to recover revenue from low-income households as well as high line losses. In this paper, a PV-Wind-Battery hybrid renewable energy system is designed to meet the energy needs of Ayitepa, a typical fishing and farming community located within the Ningo-Prampram district, about 63 km from the capital Accra with a population of 1,375 people, residing within 194 households in 138 houses. The community's daily electrical load was estimated to be 100 kW, with a cumulative daily primary load of 180 kWh/d consisting of residential, commercial, and industrial loads such as houses, schools, flour mills, a health clinic, and cold stores. HOMER software was used to perform analysis to determine the optimum hybrid renewable energy system configuration for the community. It was observed that the configuration comprising a battery bank (3,050 kWh), converter (66 kW), PV (180 kW), and wind turbine (50 kW) was the best configuration sizing required to meet Ayitepa's load. The hybrid system LCOE and NPC was estimated at $0.405/kWh and $1,825,558.00 respectively. Also, the hybrid system had an initial capital cost of $957,800.00. The operating cost associated with this hybrid system was about $46,938/yr. These costs, however, reduced with increasing capital subsidy.

Keywords: Hybrid Renewable Energy System, HOMER Software, Converter, Battery Bank, Distribution System, Electrical Load

1. Introduction

Electricity has become an essential tool that has aided in improved living standards and also the socio-economic development of many rural and peri-urban communities worldwide.

"A direct relationship exists between the absence of adequate energy services and many poverty indicators such as infant mortality, illiteracy, life expectancy, and total fertility rate. Inadequate access to energy also exacerbates rapid urbanization in developing countries, by driving people to seek better living conditions" [1].

"Without access to electricity, the pathway out of poverty is narrow and long" [2]. Between 1990 and 2017, the rate of access to electricity among populations around the globe recorded a gradual growth. As of 2017, approximately 89% of the world's population had access, up from 71% in 1990. *"Countries with the highest levels of poverty tend to*

have lower access to modern energy services, a problem that is most pronounced in Sub-Saharan Africa and South Asia, where a large share of the population depends on traditional biomass for cooking and heating and lacks access to electricity" [2].

As of 2018, the rate of electrification in the Sub-Saharan region of Africa stood at 45% [3], a significantly low rate compared with Europe (100%), North America (100%), and other parts of the world, with about 600 million people in that region still without access to electricity, representing more than two-thirds of the global aggregate.

About half of this population resides in five countries, namely; Nigeria, DR Congo, Ethiopia, Tanzania, and Uganda.

To meet or reduce the demand for electricity generated by the growing demand for access, two key strategies can be explored: construction of primary substations and extension of the distribution network to supply electricity to urbanized, peri-urbanized, and rural communities; as well as provision of community-level renewable energy distributed generation, mini-grid or micro-grid systems to remote and island communities through off-grid electrification. These two approaches call for different capital needs, supply different population densities, and deploy different technologies.

Traditionally, the supply of electricity to the general populace involves the construction of power generating plants and the extension of high-voltage transmission lines and distribution networks across the nation. In recent years, more than 1.7 billion people globally, many living in urban areas, have gained access to the national grid. On the contrary, access rates in small, isolated, and island areas have been slow, primarily due to insufficient generation capacity to meet growing loads, aged or dilapidated transmission and distribution infrastructure occasioned by poor maintenance practices, high supply costs, coupled with the weak financial position of the utilities and their inability to recover revenue from low-income households.

Other considerations such as high line losses, technical feasibility, and economic parameters such as the Net Present Cost and Internal Rate of Return means that island and remote communities with small populations and low consumption patterns are generally the last to be considered for connection to the grid.

Alternatively, electricity, especially on remote and island communities can be extended through off-grid electrification, which entails relatively smaller grids compared to traditional grid electrification. Another approach is to utilize mini-grids, which are integrated local generation, storage, and distribution systems usually isolated from the grid, but within a confined geographical space. These systems have installed capacity less than 10 MW, are typically operated locally and serve households within a radius of 50 kilometres [2].

Similarly, "micro-grids", which are smaller units, usually operating at lower voltage levels over a range of 8 kilometres at a capacity less than 100 kW can be deployed.

These off-grid electrification systems are typically fuelled by renewable energy sources like hydro, solar PV, wind, tidal, and biomass or fossil fuels such as diesel, or a blend of two or more of these, known as a Hybrid Renewable Energy System, (HRES).

"To deliver universal energy access by 2030, decentralized options are the least-cost option for 60 per cent of people currently lacking access" [4].

It is worth noting though that around three-quarters of global greenhouse gas emissions are attributable to fossil fuel combustion for electricity generation. According to the Climate Analysis Indicators Tool, *"the primary sources of global greenhouse gas emissions are electricity and heat (31%), agriculture (11%), transportation (15%), forestry (6%) and manufacturing (12%). Energy production of all types accounts for 72% of all emissions".*

"Not only is energy generation the primary catalyst of climate change, the combustion of fossil fuels and biomass also has a major effect on public health, with at least five million deaths attributed to air pollution each year" [5].

This paper therefore aims at designing an optimized solar PV/Wind hybrid power system to meet the energy needs of a typical rural community such as Ayitepa in Ghana.

2. Materials and Methods

2.1. Description of Study Area

Ayitepa is a predominantly fishing and farming community located within the Ningo-Prampram district about 63 km east of Ghana's capital, Accra. The community lies between coordinates 5° 47' 0" North, 0° 16' 0" East, with a population of 1,375 people, residing within 194 households in 138 houses [6].

Since part of the Ayitepa community is already connected to the national grid, the current electrical load requirement was retrieved hourly from the existing metered distribution transformer installed to provide power to the community. Nonetheless, loads of homes with or without electricity were determined through a field survey via a formal interview to analyze the different electrical equipment currently owned by households as well as those they estimate would be owned by them in the future when the rest of the community is electrified. Additionally, the current consumption pattern of households already connected to the grid was considered in the estimation.

Ayitepa's electrical load is divided into three categories: residential (home) load, industrial load, and community load.

2.2. Resource Assessment

Hybrid Optimization of Multiple Energy Resources (HOMER), developed by the National Renewable Energy Laboratory (NREL) in the United States, is a software application used to develop and evaluate technical and financial options for off-grid and grid-connected power systems for remote, stand-alone, and distributed generation systems [7, 8].

By using HOMER, it is much easier to design a system that is capable of matching the energy availability from different technologies (such as wind, solar, and diesel generators) with the local load profile [9, 10].

HOMER software requires Solar Global Horizontal Irradiance (GHI) and wind speed for simulation and optimization of the hybrid power system. From the data retrieved from NASA Surface Meteorology and Solar Energy database, Ayitepa community has significant solar and wind potential to meet its electricity requirements.

2.2.1. Solar Resource Assessment

The average monthly solar GHI data for Ayitepa was obtained from the NASA Surface Meteorology and Solar Energy database using HOMER software with reference to the coordinates 5° 47 '0' North, 0° 16 '0' East of the area under analysis. Over a 22-year duration, the NASA database provided monthly average solar global horizontal radiation values (between July 1983 and June 2005). To measure the photovoltaic (PV) array capacity for each hour of the year, HOMER uses the solar radiation data, then outputs the average monthly radiation and clearness index of the baseline data in the solar resource table, as shown in Table 1 [11].

Table 1. *Monthly Average Solar Global Horizontal Irradiation Data for Ayitepa Community.*

Month	Clearness Index (%)	Daily Radiation (kWh/m^2/day)
January	0.614	5.78
February	0.612	6.09
March	0.572	5.94
April	0.549	5.72
May	0.526	5.32
June	0.476	4.71
July	0.521	5.20
August	0.518	5.31
September	0.512	5.29
October	0.564	5.64
November	0.600	5.69
December	0.604	5.56

2.2.2. Wind Resource Assessment

Average wind speed was obtained from NASA's Surface Meteorology and Solar Energy database at 50 m above the surface of the earth over ten years via the HOMER software (See Table 2 and Figure 1) [11].

Table 2. *Monthly Average Wind Speed Data for Ayitepa Community.*

Month	Average Wind Speed (m/s)
January	3.72
February	3.99
March	4.05
April	3.6
May	3.18
June	3.25
July	4.47
August	4.63
September	4.6
October	3.71
November	3.96
December	3.33

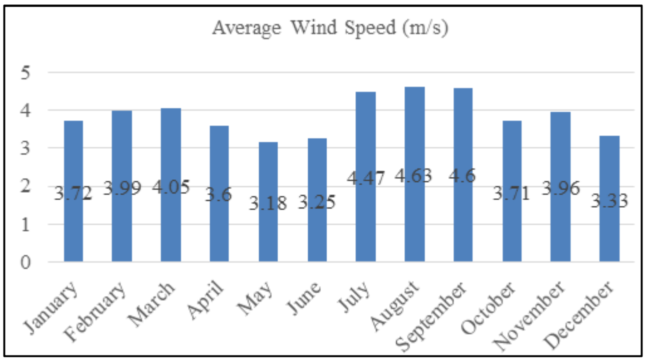

Figure 1. *Monthly Average Wind Speed Data for Ayitepa Community.*

2.3. Resource Modelling and Simulation of System Components

The proposed mini-grid system comprises a solar PV array, wind turbine, battery, converter, and distribution system. In this regard, the component's technical specification and cost details determine the project viability. Figure 2 shows the simulated model for Ayitepa Community.

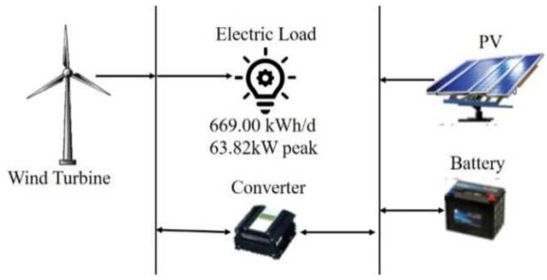

Figure 2. *Simulated Model for Ayitepa Community.*

2.3.1. Solar PV Array

Through a process known as the photoelectric effect, the solar cells within the PV panels transform sunlight into direct current (DC). The PV array would be ground-mounted on a fixed axis and tilted at a slope equal to the community latitude value to capture maximum solar radiation. The PV azimuth angle is zero, with an orientation towards the south. A typical PV panel lifetime of 25 years is considered. The derating factor that accounts for losses due to the influence of temperature, dust, conductor losses, shading, ageing, etc. is taken as 90%, meaning that the panel will produce 10% less power than the nominal value. Also, a ground reflectance of 20% is considered for this study. Table 3 presents the technical specification of the selected PV panel. HOMER computes the power output (PV_{output}) of the PV array using equation 1:

$$PV_{output}=C_{PV}D_{PV}\left(\frac{I_T}{I_{T,STC}}\right)\left[1+\alpha_p\left(T_c-T_{c,STC}\right)\right] \quad (1)$$

where C_{pv} = rated capacity of the PV module (kW) under standard test conditions; D_{pv} = PV derating factor (%); I_T = solar radiation incident on the module surface (kW/m^2); $I_{T,\ STC}$ = incident solar radiation at standard test conditions (1000 W/m^2); α_p = temperature coefficient of power (%/°C); T_c = PV cell temperature in °C and $T_{c,STC}$ = PV cell temperature under standard test conditions (25°C).

Table 3. *Technical Specification of Solar PV Panel.*

Parameter	Specification
Brand Name	Sunpal
Nominal Maximum Power (P_{max})	320 W
Cell Type	Monocrystalline
Product Type	Crystalline Silicon PV Module
Maximum Operating Voltage (V_{mp})	37.4 V
Maximum Power Current (I_{mp})	8.56 A
Open Circuit Voltage (V_{oc})	45.8 V
Short Circuit Voltage (I_{sc})	9.07 A
Module Efficiency	16.5%
Operating Temperatures	-40 °C~+85 °C
Temperature Coefficient of P_{max}	-0.39 %/°C
Temperature Coefficient of V_{oc}	-0.29 %/°C
Temperature Coefficient of I_{sc}	0.05 %/°C
Nominal Operating Cell Temperature	45±2 °C

2.3.2. Wind Turbine

In this paper, a generic wind turbine with a rated capacity of 10 kW is selected. This wind turbine has a hub height of up to 25 m high and a rotor diameter of 21 m. The cut-in speed and cut-off speeds are 2.3 m/s and 24 m/s, respectively. The wind turbine has a lifetime of 25 years.

2.3.3. Battery Specification

Electricity production generation from PV is only available during the day. Therefore, to supplement power generation from wind turbines, a battery bank facility is needed to ensure a consistent power supply. The battery stores excess energy generated from the system to meet the electricity demand of the community, even when the PV and wind turbine power supply is unreliable and inaccessible. Table 4 presents the technical specification of the selected batteries. HOMER calculates the autonomy of the storage bank A_{batt} and the battery life R_{batt} using the equations (2) and (3) as follows (HOMER Energy):

$$A_{batt}=\frac{N_{batt}V_{nom}Q_{nom}\left(1-\frac{q_{min}}{100}\right)\left(24\frac{h}{d}\right)}{L_{prim,ave}\left(1000\frac{Wh}{kWh}\right)} \quad (2)$$

$$R_{batt}=\min\left(\frac{N_{batt}Q_{lifestime}}{Q_{thrpt}}, R_{batt,f}\right) \quad (3)$$

where N_{batt} = number of batteries in the storage bank; V_{nom}= nominal voltage of single storage (V); Q_{nom}= nominal capacity of single storage (Ah); q_{min}= minimum state of charge of the storage bank (%); $L_{prim,\ ave}$= average primary load (kWh/d); N_{batt} = battery bank's number of batteries, $Q_{lifetime}$ = lifetime throughput of a single battery, Q_{thrpt} the annual throughput, and $R_{batt,f}$ = battery's float life.

Table 4. *Technical Specification of Batteries.*

Parameters	Specification
Nominal Voltage	12 V
Nominal Capacity	1 kWh
Maximum Capacity	83.4 Ah
Capacity Ratio	0.403
Roundtrip Efficiency	80 %
Maximum Charge Current	16.7 A
Maximum Discharge Current	24.3 A
Maximum Charge Rate	A/Ah

2.3.4. Power Converter Specification

The power converter has inversion and rectification units, ensuring uniform energy flow between direct current and alternating current. The inversion unit converts Direct Current (DC) to Alternating current (AC). Similarly, the AC is converted to DC by the rectification unit. The converter has an efficiency of 95% and a lifespan of 15 years.

2.4. Components Cost Details

Capital cost is the purchased price of the component while replacement cost represents the cost of replacing a component at the end of its lifetime. The operating and maintenance cost is the annual cost of operating and maintaining the component. Table 5 presents cost details for PV, battery, wind turbine, and converter economic input data while Table 6 gives the summary of economic input parameters.

Table 5. *Summary of Components Cost Details.*

Component	Capital Cost	Replacement Cost[a]	O&M Cost
PV Array	$850/kW[b]	$0/kW	$8/kW/year[d]
Wind Turbine	$2500/kW[c]	$0/kW	$750/yr[d]
Battery	$200/kWh[b]	$180/kWh	$2/kWh/year[d]
Converter	$300/kW[b]	$250/kW	$4/kW/year[d]

[a]Replacement costs are estimated based on market trends and technological development
[b]Data obtained from local suppliers such as Dutch and Company Limited, Sunpower Innovations, Tino Solutions, ABSolar Africa
[c]Data collected from international market
[d]Assumption based on the characteristic performance of the component
Op.h – operating hours

Table 6. *Summary of Economic Input Parameters.*

Parameter	Value	Source/comment
Nominal Discount rate (%)	12%	(Bank of Ghana, 2019)
Expected Inflation (%)	9.3	(Bank of Ghana, 2019)
Project lifetime (years)	25[a]	Typical project lifetime used in other projects are 20-25 years
Distribution cost ($)	50,000[b]	Costs needed for the development of mini-grid distribution. Computed using an estimated inter-household distance of 20 m. Cost of distribution line per metre was obtained from the government mini-grids developer, Trama TecnoAmbiental (TTA, 2017)
Distribution System O&M Cost ($/year)	1,500[c]	Estimated cost of maintaining distribution system

[a]Typical project lifetime used in other projects are 20-25 years
[b]Cost needed for mini-grid. Computed using an approximate 20 m inter-household gap. Data obtained from the government mini-grids developer, Trama TecnoAmbiental
[c]Data collected from international market

2.5. Key Economic Metrics

In this analysis, NPC and LCOE are the main economic performance indicators to be considered for the project's viability. The system's NPC takes into account all the expenses borne by the system during its lifetime, minus the present value of all the income that the system earns over its lifetime. HOMER software calculates the total NPC, CNPC using equation 4 [12].

$$C_{NPC}=\frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \quad (4)$$

where $C_{ann,tot}$ = total annualized cost; i = annual real interest rate (the discount rate); R_{proj} = project lifetime and CRF = capital recovery factor which is given by equation 5 as [12],

$$CRF(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \quad (5)$$

where i = annual real interest rate and N = number of years.

HOMER software uses equation 6 to calculate the Levelized Cost of Energy (LCOE) in $/kWh [12].

$$LCOE=\frac{C_{ann,tot}}{E_{prim}+E_{def}+E_{grid,sales}} \quad (6)$$

where $C_{ann,\ tot}$ = total annualized cost; E_{prim} and E_{def} = total amounts of primary and deferrable load, respectively; $E_{grid,\ sales}$ = amount of energy sold to the grid per year.

2.6. Sensitivity

Table 7. *Parameter Ranges for Sensitivity Analysis of the Optimal System.*

Input variable	Unit	Sensitivity ranges
Discount Rate	%	6, 8, 10, 12[a], 13, 14
Capital Subsidy	%	0[a], 25, 50, 75, 100
Battery Costs	%	-5, -10, -15, -20, +5, +10, +15
PV Cost	%	-5, -10, -15, -20, +5, +10, +15
Wind Turbine Cost	%	-5, -10, -15, -20, +5, +10, +15

[a]Nominal value used for analysis.

Sensitivity Analysis aims to examine the performance of the system under the variability of different parameters with respect to the ideal system. For the optimized systems, the effect of discount rate, capital subsidy, PV, battery, and wind turbine costs on the LCOE and NPC were considered in the sensitivity analysis. The parameter ranges for sensitivity analysis of the optimal system is given in Table 7.

2.7. HOMER Software Input Data

HOMER software performs simulation and optimization of the proposed hybrid power system with input data such as electricity demand, renewable resources, component type and lifetime as well as economic parameters. The capital cost reflects the original purchasing price of the system, while the replacement cost is the cost of replacing the components at the end of their lifetime, whereas operating and maintenance cost is the annual cost of operation and maintenance. Cost parameters, as well as other economic input data, are provided in Tables 5 and 6.

3. Results and Discussions

3.1. Community Electrical Load

A field survey conducted by interview showed that household sizes range between 3 to 7 family members, while house sizes vary from 1 to 4 bedrooms. An average of 2 rooms per household with a household size of 5 and a total of 200 households are rated for consideration in this analysis. With a peak load demand of 100 kW, the cumulative daily primary load of Ayitepa is forecast at 180 kWh/d.

3.2. HOMER Software Results

The HOMER software algorithm performed an analysis for the optimum solution among the various parameters considered for the estimated electricity demand. Table 8 presents results from HOMER suitable for the development of a mini-grid for the Ayitepa community. The feasible solutions were ranked according to NPC and LCOE. It can be observed that the configuration comprising PV (180 kW), wind turbine (50 kW), battery bank (3,050 kWh), and converter (66 kW) is the best configuration sizing required to meet Ayitepa's load. The hybrid system LCOE and NPC is estimated at $0.405/kWh and $1,825,558.00. Also, it has an initial capital cost of $957,800.00. The operating cost associated with this hybrid system is about $46,938.33/yr. Detailed technical and economic performance from this mini-grid power system is presented in the sections below.

Table 8. *HOMER Optimization Results.*

PV (kW)	Wind Turbine (kW)	Battery (kWh)	Converter (kW)	LCOE ($/kWh)	NPC ($)	Operating Cost ($/yr)	Initial Capital ($)
180	50	3050	66	0.4047	1,825,558.00	46,938.33	957,800.00

3.3. Technical Performance of Solar PV/Wind Mini-Grid Power System

The overall electricity generated from PV/Wind hybrid power system is about 402.903 MWh/yr. About 243.982 MWh/yr of electricity is consumed by the community's primary loads while 122.163 MWh/yr of excess electricity is generated and unused. The unmet load is about 0.08% with an annual capacity shortage of about 0.1%. The annual capacity shortage falls below the maximum value of 0.5 – 5% for mini-grid power systems as suggested by [13]. Figure 3 shows the monthly PV and wind turbine electricity generation. It can be observed that electricity generated by each power system varies year-round. Electricity generation from PV dominates over the wind turbine due to the high solar irradiation and low wind speed available at Ayitepa. It can also be observed that electricity generation from both PV and wind turbine is low in April, May, and June. During these periods, Ayitepa experiences frequent rains with a cloudy atmosphere.

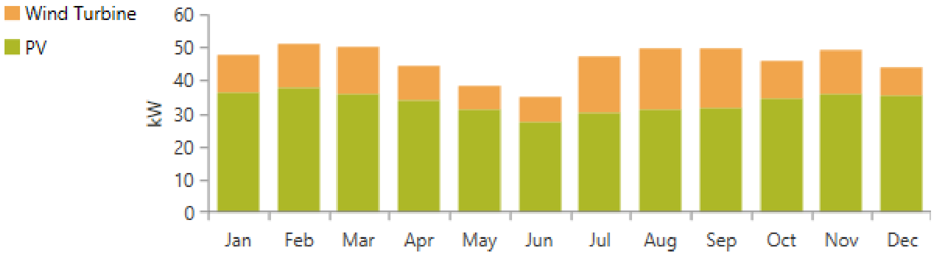

Figure 3. *Average Monthly Electricity Generation from PV and Wind Turbine.*

3.4. Solar PV Array

The PV-rated capacity is 180 kW. It generates a mean output and maximum output of 33.4 kW and 175 kW. PV capacity factor is about 18.6% with about 120% PV penetration. PV would operate for 4,380 hrs/yr and would yield a Levelized cost of $0.0332/kWh. Figure 4 displays the average PV power output for Ayitepa. It is observed that PV production is low from April – September. This low power production is caused by seasonal rainfalls that Ayitepa experiences within that period. Within the remaining months, Ayitepa experiences a relatively dry season, with a clear atmosphere and high sunshine hours with high solar irradiation. PV power production is effective from 6:00 – 18:00 throughout the year, as displayed in Figure 5.

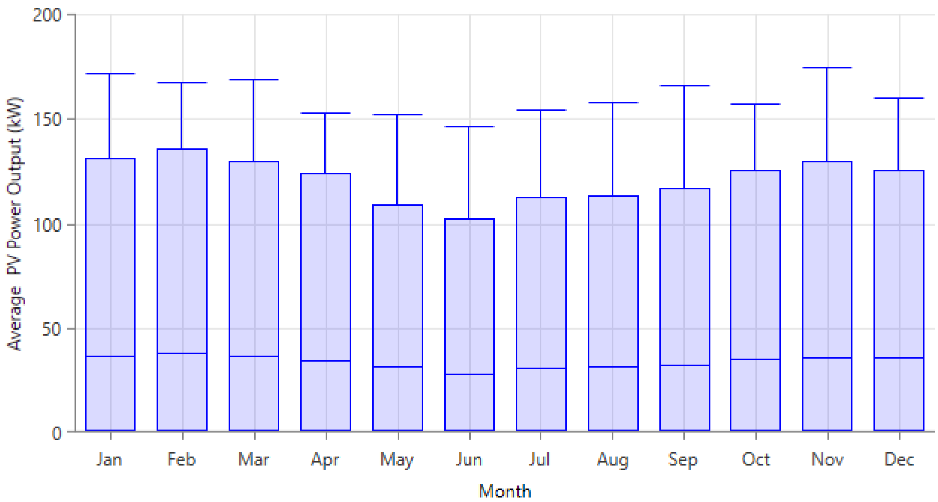

Figure 4. *Monthly Average PV Power Output.*

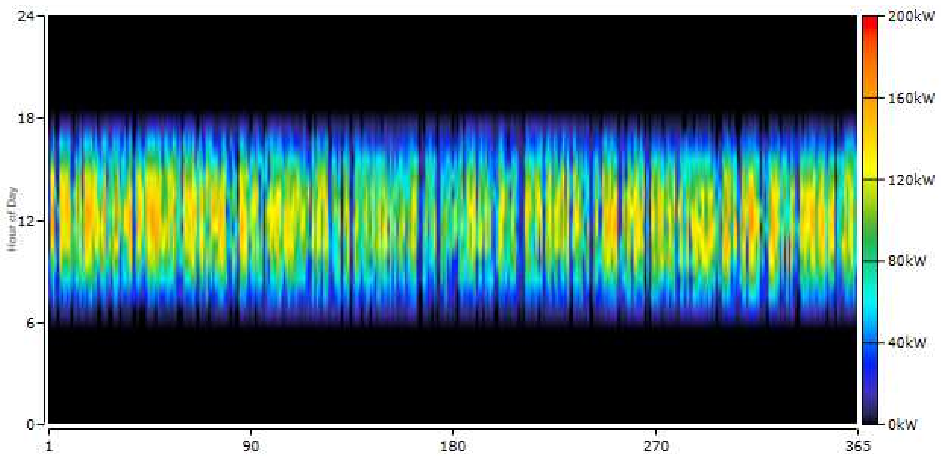

Figure 5. *Yearly Profile for PV Power Production.*

3.5. Wind Turbine

The system is comprised of 5 wind turbines, each with a rated capacity of 10 kW, generating a total of 110.304 MWh of electricity annually, with a mean output power of 12.6 kW. The wind turbine operates for 7,428 hrs/yr and is expected to yield a levelized cost of $0.0953/kWh. Furthermore, the wind turbine shows a good capacity factor of 25.2%, which is suitable for wind power investment. Power generation from the wind turbine is low for May, June, and December, as shown in Figure 6. In these months Ayitepa experiences a low wind speed below 3.5 m/s which affects power output. Also, power production is high for July – September because of good wind speeds in that period (see Figure 7).

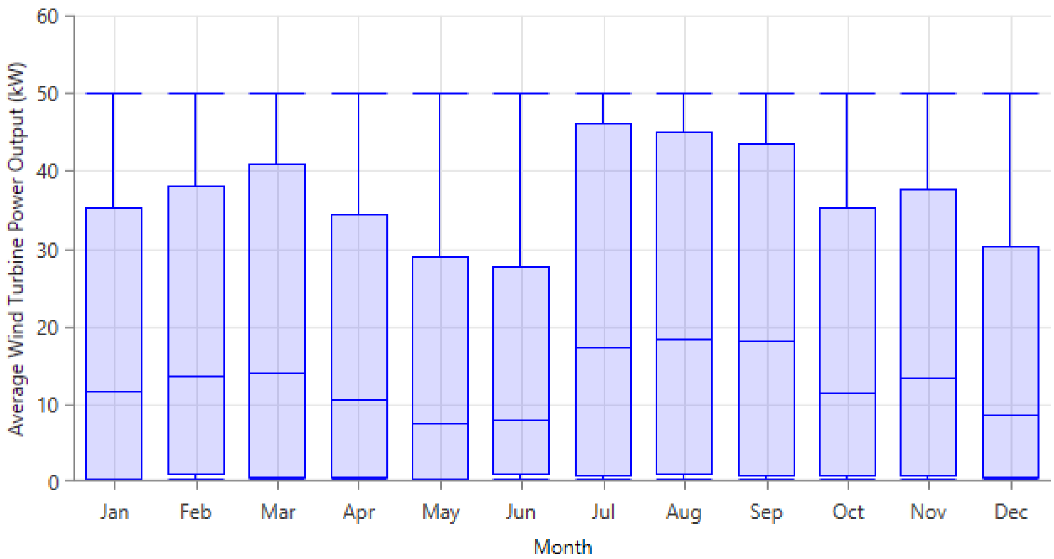

Figure 6. *Monthly Average Wind Turbine Power Output.*

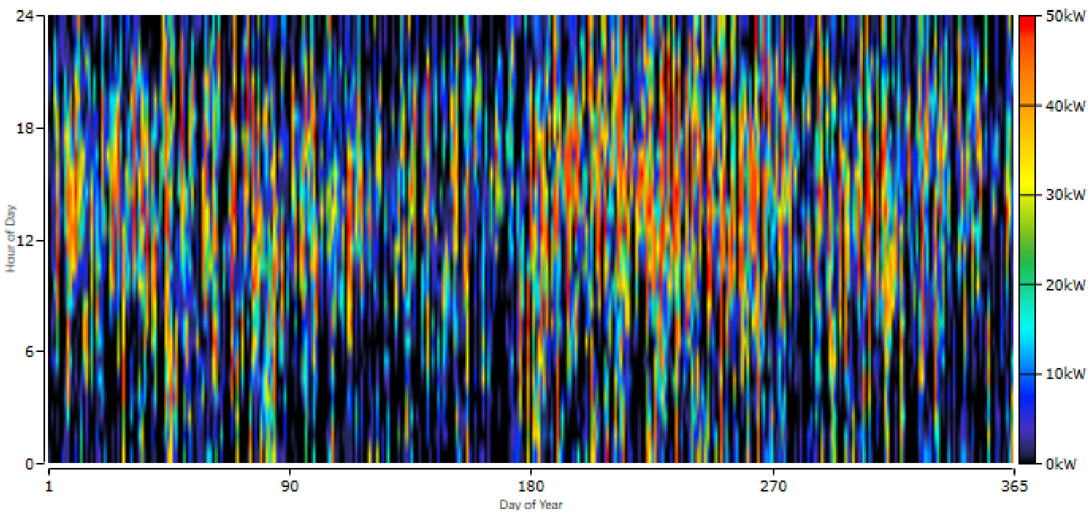

Figure 7. *Yearly Profile for Wind Turbine Power Output.*

3.6. Battery Bank Optimal Performance

Table 9 presents the technical performance of the battery bank. State of Charge (SOC) defines how completely a battery is charged; this is the opposite of discharge depth. A 100% SOC means that the battery is fully charged, while the battery is empty at 0%. Figure 8 shows that the battery bank SOC lies between 38% - 65% for May, July, and August throughout the day. The SOC is about 80 – 100% between 12:00 – 17:00 throughout the year except for May, June, and August. This high SOC is due to PV charging the battery. Furthermore, the SOC is about 60 – 80% from 18:00 – 11:00, mainly caused by the battery bank discharging energy and supplementing the wind turbine to meet electricity demand due to the absence of solar irradiation. Figure 9 displays the average monthly battery SOC.

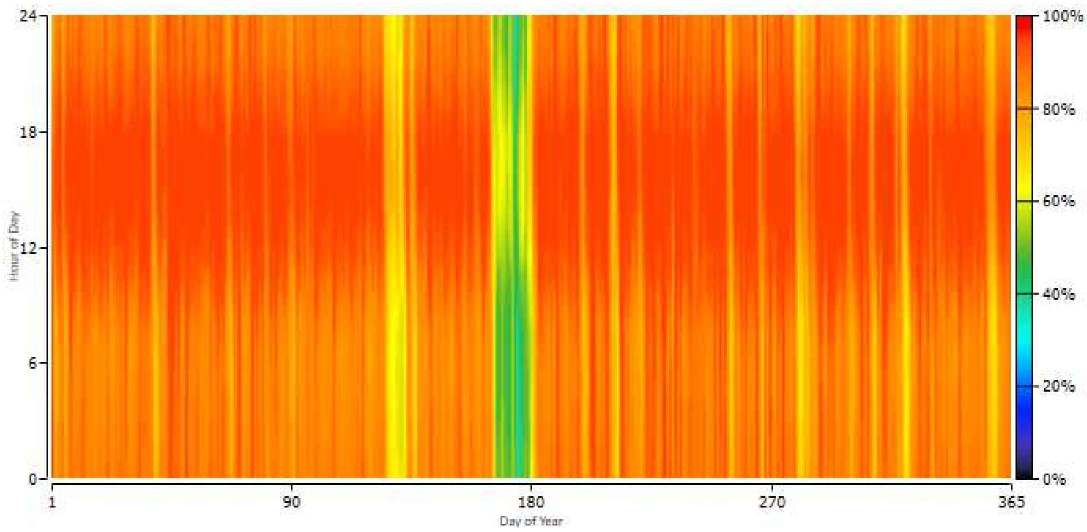

Figure 8. *Yearly Profile of Battery Bank Output.*

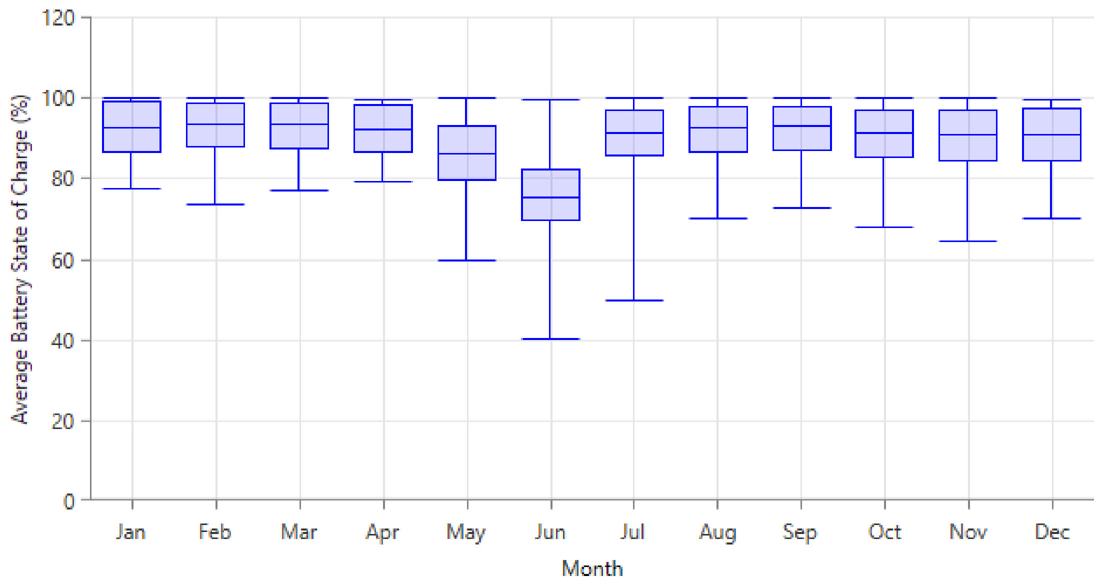

Figure 9. *Monthly Average Battery State of Charge.*

Table 9. *Performance Parameters for the Battery Bank.*

Parameter	Value
Battery Bus Voltage	12 V
Nominal Capacity	3.052 MWh
Usable Nominal Capacity	1.831 MWh
Life Throughput	1,238.2 MWh
Annual Throughput	123.82 MWh/yr
Energy In (Charge)	138.041 MWh/yr
Energy Out (Discharge)	110.746 MWh/yr
Losses	27.65 MWh/yr
Autonomy	3 days
Expected Life	10 years

3.7. Power Converter

The power converter performs both inversion and rectification. The converter converts DC to AC through inversion and AC to DC through rectification. Table 10 presents the power converter output.

Table 10. *Power Converter Output Parameters.*

Parameter	Inverter	Rectifier
Rated Capacity	66 kW	66 kW
Capacity Factor	27.4%	18.4%
Hours of Operation	7,084 hrs/yr	924 hrs/yr
Energy In	165.585 MWh/yr	11.837 MWh/yr
Energy Out	157.305 MWh/yr	10.654 MWh/yr
Losses	8.279 MWh/yr	1.184 h/yr

3.8. Economic Analysis

The cost overview of the hybrid power system is presented in detail in this section. The system's overall costs include capital, replacement, and operating costs.

Figure 10 displays the cost breakdown of the system. In summary, the system has an initial capital cost of $957,800.00. The operating cost associated with this hybrid system is $46,938.33/yr, with the salvage cost, which represents the value remaining in a component of the power system at the end of the project lifetime amounting to $280,000.00.

A breakdown of the cost of each system component over the project lifetime is outlined in Figure 11.

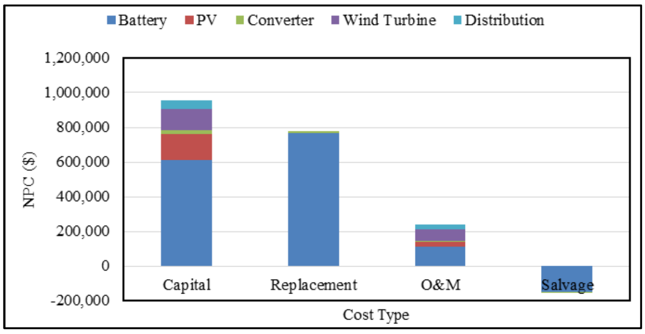

Figure 10. *Cost Breakdown of Hybrid Power System.*

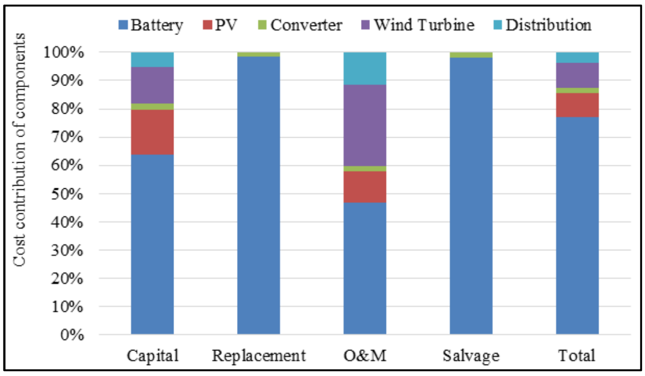

Figure 11. *Cost Contribution of Components.*

3.9. Sensitivity Analysis

Sensitivity tests were performed to examine the impact of adjustments in several key variables on the system's financial parameters. The discount rate is a significant parameter in the financial analysis of investment projects in general. It is used in the discounted cash flow analysis to calculate the value of the investment based on the estimated future cash flows. Based on the philosophy of time value of money, the discounted cash flow analysis aims to ascertain the feasibility or sustainability of the project by determining the current value of the expected investment returns using the discount rate. The discount rate applied in the base case is derived from the interest rate charged by the Central Bank for loans granted to commercial banks and other financial institutions in Ghana. Foreign financial institutions may offer lower discount rates.

In view of this, lower interest rates of 6%, 8%, and 10% were considered in the sensitivity analysis. Additionally, higher discount rates of 13% and 14% were added to the sensitivity analysis due to the risk of uncertainties in the financial system. The effect of the discount rate on NPC and LCOE is displayed in Figure 12. The base case scenario discount rate is 12%. At a discount rate of 10%, LCOE reduces by 10.1%, and NPC increases by 10.2%. Using a lower discount rate of 6% reduces LCOE by 30% and increases NPC by 30.8%. Furthermore, a higher discount rate of 14% increases LCOE by 10.1% and reduces NPC by 8.9%. With rising discount rates, NPC declines, while LCOE increases.

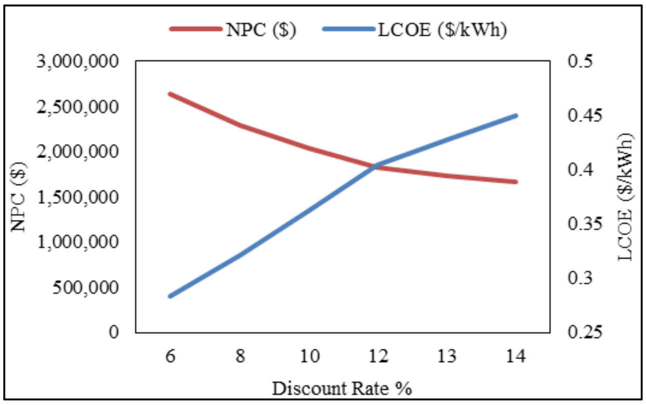

Figure 12. *Effect of Discount Rate on NPC and LCOE.*

3.10. Effect of Capital Subsidy on Financial Indicators

The sensitivity analysis also considered the effect of capital subsidy on the NPC and LCOE. Capital subsidies of 25%, 50%, 75%, and 100% were considered while operating costs were kept constant as in the base scenario.

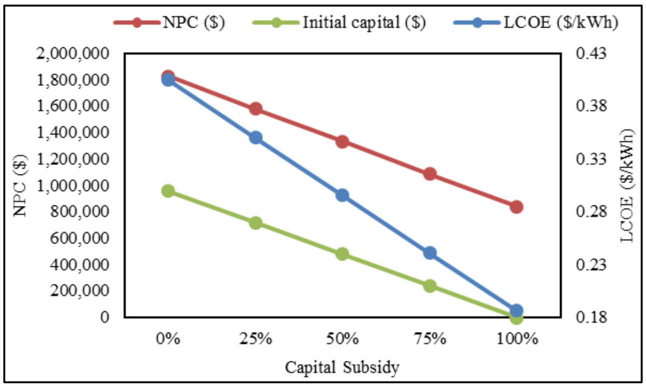

Figure 13. *Effects of Capital Subsidy on NPC and LCOE.*

It can be observed in Figure 13 that the Net Present Cost (NPC), as well as LCOE, decreases with increasing capital subsidy. When the capital cost of the project was subsidized by 25%, 50% and 75%, the NPC declined to $1,579,175.00, $1,332,793.00 and $1,086,410.00 respectively whiles LCOE reduced to $0.350, $0.295 and $0.241 respectively. However, when the project received a 100% capital subsidy, the LCOE declined to $0.18/kWh.

4. Conclusion

Renewable energy sources such as the sun (solar), wind, biomass, hydropower, geothermal, and ocean resources are all considered modern technological alternatives for generating sustainable energy. Nevertheless, when compared to the energy provided by fossil fuels, the energy derived from these sources is insignificant.

However, in recent years, there has been a global shift away from reliance on fossil fuels and nuclear power, toward more sustainable renewable energy sources like PV and wind, especially in the power generation market, aided by governmental policy changes that have promoted increased investment in renewable energy research and growth, falling prices coupled with innovative business and financing models and increased public awareness, aimed at lowering Greenhouse Gas emissions and mitigating climate change.

In Ghana, government policies on universal access to electricity and the attainment of a 10% contribution of renewable energy in the electricity generation mix by 2030, as well as increased energy efficiency practices in residential, commercial, and industrial applications are helping to drive this transition.

This paper presents the design of a PV/Wind hybrid mini-grid system required to meet Ayitepa's estimated cumulative daily primary load of 180 kWh/d and a peak load demand of 100 kW. The configuration comprising 180 kW of PV panels, a 50 kW wind turbine, a battery bank with a capacity of 3,050 kWh and a 66 kW rated converter was determined to be the most feasible after analysis with the HOMER software. The LCOE and NPC of the hybrid system were rated at $0.405/kWh and $1,825,558.00 respectively, with an initial capital cost of $957,800.00. The operating cost of this hybrid system was about $46,938.33 per year. These costs, however, reduced with increasing capital subsidy.

5. Recommendations

A considerable market exists in Ghana for the adoption and implementation of off-grid or grid-tied hybrid mini-grid systems in rural, remote island, and peri-urban communities due to the abundance of renewable energy sources such as wind and solar (PV) within such communities. To satisfy this demand while reducing the need to construct new GHG-emitting fossil-powered thermal power plants to meet growing customer loads, the following recommendations are proffered:

1) Government should consider implementing single or hybrid renewable energy generation systems in small isolated, remote rural, island, and peri-urban communities where there exist abundant renewable energy sources rather than relying on the need to construct additional GHG-emitting fossil fuel-powered thermal power generation plants, especially where it is established after analysis that grid extension to these communities is technically or economically infeasible.
2) Implementation of the net metering policy by regulators such as the Energy Commission and PURC to enable the export of excess electricity generated (122.163 MW/yr or equivalent to 10.18 MW/month in this research) into the national grid.
3) Initiating government policies, subsidies, tax holidays, or the enactment of laws to incentivize individuals, corporate or financial institutions who promote or invest in single or hybrid renewable energy systems, especially in remote rural, island, or peri-urban communities to help minimize the high initial investment and operation costs.
4) Adequate resourcing of the Ministry of Energy's SHEP initiative to implement off-grid or grid-tied single or hybrid renewable energy systems in rural, island, remote and peri-urban communities, as envisaged in the NES master plan.

References

[1] The Parliamentary Office of Science and Technology (2002). Access to Energy In. Access, (191). Retrieved from https://www.parliament.uk/globalassets/documents/post/pn191.pdf

[2] The World Bank (2017). State of Access Electricity Report. Retrieved September 10, 2020, from http://documents1.worldbank.org/curated/en/285651494340762694/pdf/114841-ESM-PUBLIC-P148200-32p-FINALSEAROverviewWEB.pdf

[3] IEA (2019). Renewables Information: Overview, IEA, Paris. Retrieved from https://www.iea.org/reports/renewables-information-overview

[4] UN DESA (2018). Accelerating SDG 7 Achievementpolicy Brief 01 Achieving Universal Access to Electricity [Ebook] (pp. 1-11). Retrieved from https://sustainabledevelopment.un.org/content/documents/17462PB1.pdf

[5] Anon. (2021). Global Emissions Center for Climate and Energy Solutions. Retrieved 10 January 2021, from https://www.c2es.org/content/international-emissions

[6] Ghana Statistical Service (2014). Ningo-prampram Municipality, Population and Housing Census, 87.

[7] National Renewable Energy Laboratory (2010). HOMER Getting Started Guide Version 2.68, NREL.

[8] Iqbal, M. T. (2004). A Feasibility Study of a Zero Energy Home in Newfoundland, Renewable Energy, 29 (2) 277289.

[9] Designing High Reliability Power Systems for PEMEX Using HOMER (2004). Arturo Romero Paredes Rubio, World Renewable Energy Congress VIII, Denver, Colorado.

[10] Georgilakis, P. S. (2005). State-of-the-Art of Decision Support Systems for the Choice of Renewable Energy Sources for Energy Supply in Isolated Regions, International Journal of Distributed Energy Resources, 2 (2) 129-150.

[11] Anon. (2018). NASA https://www.researchgate.net/figure/Average-monthly-global-horizontal-irradiance-and-temperature-data-of-study-site-NASA_tbl1_355188433

[12] Lambert, T., Gilman, P. and Lilienthal, P. (2006). Micropower System Modeling with Homer. Integration of Alternative Sources of Energy, 379–418. https://doi.org/10.1002/0471755621.ch15

[13] Adaramola, M. S., Agelin-Chaab, M. and Paul, S. S. (2014). Analysis of Hybrid Energy Systems for Application in Southern Ghana. Energy Conversion and Management, 88 (2014), 284–295. https://doi.org/10.1016/j.enconman.2014.08.029