RESEARCH ARTICLE

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Feasibility Study and Techno-Economic Analysis of Solar PV-Biomass Hybrid Power System: A Case Study of Kajola Village, Nigeria

Ayodele Osalade, Adewale Abe, Bankole Adebanji, Taiwo Fasina, Samson A. Adeleye and Toyin Omotoso

ABSTRACT

Efficient and sustainable electric power supply is needed for effective healthcare delivery, provision of quality education system, and building of impactful social/human infrastructures. Unrestricted access to reliable and affordable electricity will improve people's welfare and enhance quality healthcare delivery globally. The need to reduce the harmful impact of Greenhouse gas emissions along with its fossil fuel emissions have necessitated the need for the numerous research interests in low-carbon power generation systems. The feasibility and techno-economic analysis of an off-grid Solar Photovoltaic (PV)/Biomass (BG)/Diesel (DG)/Battery (BB) hybrid system for a rural village-Kajola, Nigeria was conducted in this paper. Renewable energy sources (RES) parameters such as irradiation data, biomass resources, and DG parameters were collected from National Aeronautics and Space Administration (NASA)' database, Ekiti State Ministry of Agriculture and manufacturers' price lists respectively. The load demand assessment of the area was conducted and analyzed through the use of questionnaires. All the relevant data collected were used as input into the HOMER software. The optimal configuration is the PV-BG-BB combination. The Levelized Cost of Energy (COE) is $0.178/ kWh, with renewable energy fraction (RF) of 100%. This means that nearly all of the energy used by the hybrid system to meet the load is generated from renewable sources. The proposed solar PV/Biomass generator/Battery bank hybrid energy system can supply electricity to the village under consideration at an hourly average of approximately 52.7 kW and with an average daily energy need of 483.71 kWh. The study will serve as a template for all electric power system stakeholders and potential investors on the feasibility and optimal design of hybrid renewable energy system for rural electrification.

Keywords: Biomass, off-grid, renewable energy, solar PV, sustainable energy.

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A. Osalade*
Electrical Engineering Department, Ekiti State University, Ado-Ekiti, Nigeria.
(e-mail: osaladeaj@gmail.com)

A. Abe
Electrical Engineering Department, Ekiti State University, Ado-Ekiti, Nigeria.
(e-mail: adewale.abe@eksu.edu.ng)

B. Adebanji
Electrical Engineering Department, Ekiti State University, Ado-Ekiti, Nigeria.
(e-mail: bankole.adebanji@eksu.edu.ng)

T. Fasina
Electrical Engineering Department, Ekiti State University, Ado-Ekiti, Nigeria.
(e-mail: emmanuel.fasina@eksu.edu.ng)

S. A. Adeleye
Mechanical Engineering Department, Ekiti State University, Ado-Ekiti, Nigeria.
(e-mail: adedayo.adeleye@eksu.edu.ng)

T. Omotoso
Civil Engineering Department, Ekiti State University, Ado-Ekiti, Nigeria.
(e-mail: toyintoso@yahoo.com)

Corresponding Author

I. Introduction

Access to a sufficient supply of affordable, clean, and stable electricity is a necessary condition for any nation to achieve a sustainable socio-economic and technological development. Efficient and sustainable electric power supply is needed for effective healthcare delivery, provision of quality education system, and building of impactful social/human infrastructures. As a result, a country that lacks sustainable electricity will experience slower economic growth, with a negative impact on citizens' quality of life [1].

Nigeria is a developing country with insufficient energy supply to meet the country's ever-increasing demand, as the maximum injected power supply to the national electricity grid is fluctuating between 3000 MW and 4000 MW [2], [3]. This cannot meet the urban electricity demand, let alone rural areas that are difficult to reach due to poor topography, long distances from the grid, and the economic viability constraints of electricity distribution companies' (DisCos'). It appears that no matter how much effort is expended, the problem persists simply because electricity demand continues to rise while supply remains stagnant or declining [4]-[6].

Nigeria, particularly its rural dwellers, suffers from some of the world's worst forms of electricity deprivation [7]. Many rural communities are completely off the grid; even for those that are connected to the grid, electricity is frequently unreliable, and blackouts are frequent. Some of these rural areas are either very far from the grid or under-populated, thereby making grid extension to these areas absolutely not economically viable when compared to using Renewable Energy System (RES) technology as an alternative.

The International Energy Agency's (IEA) [8] Africa Energy Outlook report recommended decentralized solutions as the most cost–effective way to provide power to more than half of the country's 77 million people by 2030. As a result, there is a need to diversify in order to achieve a broader

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electricity supply mix, which will ensure Nigeria's electricity security, particularly in rural areas. Renewable Energy System (RES) has been acknowledged globally as a potential major contributor in strengthening sustainable energy infrastructures and at the same time the most suitable an energy solution option for electrification of the rural areas. RES is vastly available in almost everywhere, clean and environmentally benign.

However, meeting the energy needs of these rural communities with a single renewable energy resource may be insufficient. Renewable energy resources are inherently stochastic. PV output varies greatly depending on insolation level, and its irradiation level changes daily. Biomass resources are also under threat. These challenges are classified as operational, economic, social, policy, and regulatory. As a result, integrating different RES together to form a hybrid power system (HPS) is a better alternative than using only one RES or national grid extension in order to enhance an efficient and reliable power supply system in these areas. HPS consists of two complementary energy generating systems, energy storage, conditioning and controlling systems. It may be combination of RES alone, non- RES or combination of both. This improves system efficiency and power supply sustainability [9]. HPS are now widely accepted as an efficient and reliable off-grid power source in remote rural areas.

Several authors have worked on RES technologies and on the application of various methodologies in solving them in almost every part of the globe, including Nigeria [10], [11], [5]. Some of them proposed the use of off-grid applications [4], [12], [13] while others proposed grid-connected solutions [10], [14].

Reference [13] worked on the feasibility and optimal design of integrating an off-grid Small hydropower (SHP)'s installations in existing water infrastructures and forming HPS involving Solar PV and DG. The results showed that the COE is \$0.1666/kWh for SHP-Solar PV-Battery-DG and \$0.290/kWh for Solar PV-Battery-DG. Reference [15] proposed a distributed generation system-based methodology for optimum sizing of a battery integrated with biomass gasifier on an un-electrified village. It uses design space method to enhance designer combination of gasifier with battery system for the load profile of the village with specific identified constraints. Sensitivity analysis was also performed to accommodate related key input parameters. Reference [16] carried out a techno-economic feasibility analysis of an off-grid Solar PV-Biogas hybrid system using HOMER software for modeling of the hybrid components. Simulation result showed that the levelized C.O.E. is \$0.236/kWh and an NPC of \$92,988 was selected as the optimal configuration.

Reference [5] investigated the feasibility of integrating SHP plants into an existing water supply dam, as well as the development of a SHP-Solar PV-DG HPS model for feasibility assessment and optimal sizing of Hybrid renewable energy systems in rural areas. Genetic Algorithm was used to determine the optimal size of the system's components for optimal configuration. The developed hybrid model was validated by comparing its results with those obtained from the software. The developed model simulation results compared favorably and were very close to those obtained using HOMER software. Reference [12] carried out a comparative analysis of an on-grid and off-grid hybrid power system with due consideration of the issues and challenges of RES growth in the country. The study identified the barriers and recommended ways of resolving the issues through effective policy formulation framework.

All of the authors discussed above, conducted research on various renewable energy resources and hybrid system topologies that could meet the energy needs of the various study areas. Very few have conducted research into biomass and solar PV using the study area. In other words, the various hybrid system setups studied differ in terms of parameters such as load demands, application, study location, vegetation, and climatic data. This research work investigated the techno-economic feasibility of an off-grid Solar Photovoltaic (PV)/Biomass/Diesel (DG)/Battery hybrid system for a rural electrification in Nigeria using Kajola village as a case study. The hybrid system is such as to minimize cost, meet load demand, improve socio-economic and well-being of the rural dwellers without negatively impacting the environment.

II. Materials and Methodology

Renewable energy sources (RES) parameters such as irradiation data, biomass resources, DG parameters were collected from NASA's websites, Ekiti State Ministry of Agriculture and manufacturers' price lists respectively. The load demand assessment of the area was conducted and analyzed through the use of questionnaires. All the relevant data collected were used as input into the HOMER software. The software was used to model the hybrid components as in Fig. 1. A Garmin Etrex 10 Handheld Global Positioning System (GPS) device was used to geotag the households and community for easy identification and to extract the Google Earth map. This is as shown in Fig. 2.

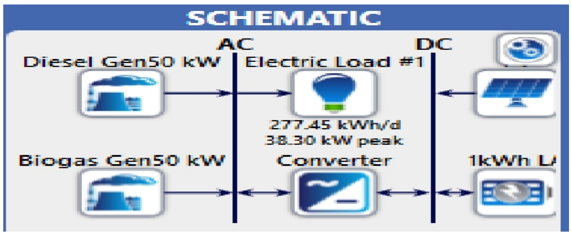


Fig. 1. Solar PV-biomass-battery-diesel system model.

Fig. 2. Garmin etrex 10 handheld global positioning system (GPS) device.

A. Description of the Study Area

The study location is Kajola village, Nigeria. The GPS aerial view of the village is shown in Fig. 3. Geographically, the village lies on Latitude: N07^0 42.368', Longitude E005^0 24.331'. The total load demand of the village is estimated to be 22.5 kW. The population is scanty. The villagers are pre-occupied with farming and animal husbandry. They depend on kerosene lamps, firewood, candles and torches for lighting and energy needs. It also has some small/medium business enterprises.

Fig. 3. Geo-location and topological aerial view of Kajola, Nigeria.

B. *Data Acquisition for the Study Area*

A daily solar radiation data and clearness index for the study area was obtained from NASA's global satellite database using their respective coordinate latitudes and longitudes (NASA, 2022). Annual Ekiti State produce / plant and animal biomass data was taken from outcome of the questionnaire and the records of Ekiti State Ministry of Agriculture and Food Security, Produce Department.

C. *The Village Energy Demand*

The electrical load profile derived from the use of (1).

$$PL = (\text{Pr}) \times (Na) \times (t) \quad (1)$$

where P_L is the primary load (kWh/d), P_r is the appliance power rating (W), N_a is the number of appliances, t is the time of use (hr/d).

The load profile summary is as in Table I. The daily load profile of the village to be met by the proposed hybrid system as synthesized in HOMER software is shown in Fig. 4. Average daily energy demand for the area is 483.71 kWh and a daily average power of 52.75 kW, while 38.2 kW is the peak load

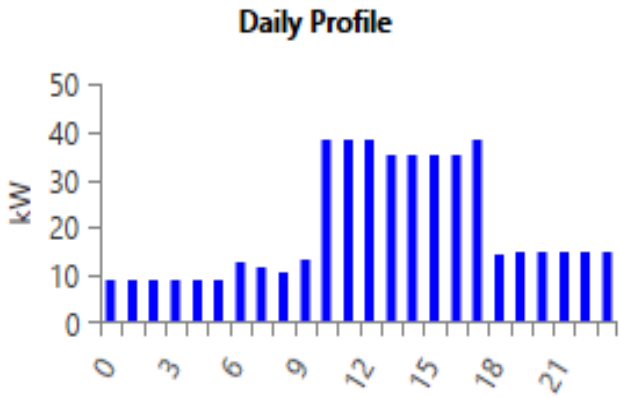


Fig. 4. Typical daily load profile pattern for Kajola village, Nigeria.

D. *Renewable Energy Resources Assessment*

1) *Solar Energy*

Solar irradiations for 10 years were obtained from the NASA's database based on the study area location. The Global Horizontal Radiation (GHR) pattern is as in Fig. 5. The average annual solar irradiation in the village ranges between 3.76 and 5.47 kWh/m^2/day and overall average of 4.94 kWh/m^2/day. The dry period spans between November and March, and the wet season lasts from April to June. As a result of the rainy period, the months of July and September have very low solar irradiation.

TABLE I: ESTIMATED ENERGY DEMAND FOR KAJOLA VILLAGE, NIGERIA

Category	Final use	Load Type	Rated Power (W) (a)	Quantity (No) (b)	Operating (Hr/day)	Usage (hr/day)	Load (kWh/day)	A x b (W)
Residential	Households	Lighting	5	62	16.00-06.00	14	4.34	310
		Radio	5	44	17.00-22.00 05.00-07.00	7	1.54	220
		Telephone	3	72	17.00-19.00	2	0.432	216
		Fan	50	39	12.00-05.00	17	33.15	1950
		Refrigerator	700	1	00.00-24.00	24	16.8	700
		Television	230	25	16.00-23.00	7	40.25	5750
Commercial	Community	Water well pump	1000	0	16.00-19.00	3	0	0
		Streetlight	100	6	18.00-06.00	12	7.2	600
		School	2700	1	08.00-16.00	8	21.6	2700
		Health centre	5400	1	06.00-12.00 19.00-06.00	17	91.8	5400
		Worship centre	1800	3	05.00-07.00 17.00-19.00	4	21.6	5400
Industrial	Factory	Milling machine	1500	3	07.00-17.00	10	45	4500
		Factory machine	25000	1	09.00-17.00	8	200	25000
Estimated Total							483.712	52746
Approximated load							500	

2) Biomass

The primary data of the available biomass resources of the village were provided by the farmers and residents in the village. This was accomplished through the use of questionnaires and comprehensive field surveys to assess the total biomass production of the village. The biomass availability in the village was determined by the type of vegetation and different basic parameters like tree height, stem diameter and density. The findings were extrapolated and estimated over a larger area of land in order to formulate equations to calculate biomass availability. Fig. 6 showed the village biomass resources pattern.

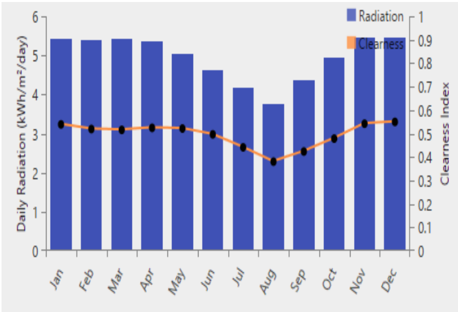


Fig. 5. Daily average global horizontal radiation pattern of kajola village, Nigeria.

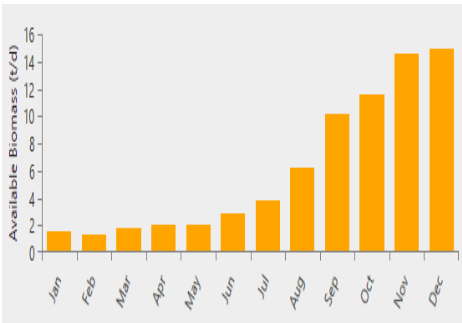


Fig. 6. Kajola monthly average available biomass data pattern.

E. Renewable Energy Resources Assessment

The mathematical model for each of the Hybrid Power System (HPS) component was discussed in this subsection. The symbols and the meanings are as in in Table II.

TABLE II: SYMBOLS AND MEANINGS

Symbols	Meanings
G(t)	Hourly irradiance in kWh/m^2
A	Surface area in m^2
P	Penetration level factor of PV
η_{PVG}	PV generator efficiency
η_{pc}	Power conditioning efficiency (1 if MPPT is used)
β	Temperature coefficient ((0.004-0.006) per °C)
η_r	Reference mod. efficiency
Tcref	Reference cell temp. °C
T_a	Ambient temp. °C
NOCT	Nom. operating cell temp. in °C
G_t	Solar irrad. in tilted module plane (W/m2)
800	Solar irradiance under Performance Test Condition (PTC).
$Kcal$	Calorie of the dry biomass resource available in the study area
E_{BGG}	Energy output of the biogas digester
η_{BGG}	System conversion efficiency
CV_{BGG}	Biogas digester calorific value (4700$Kcal/kg$) and it is divided by 860 to convert kcal to kWh (1 kWh = 860 $Kcal$)

TABLE II: SYMBOLS AND MEANINGS *(CONT)*

Symbols	Meanings
h_{BGG}	Operating hours of the biogas generator (alternator) per day
P_{in}	Inverting power express in kVA
P_{ch}	Period power demand
η_{in}	Efficiency of the inverter
N_{batt}	Battery quantity
V_{nom}	Battery nominal voltage
Q_{nom}	Nominal battery capacity
q_{min}	Minimum battery state of charge
$L_{prim,ave}$	Average electric load
X_{batt}	Batteries in the battery bank
$Y_{lifetime}$	Battery's lifetime throughput
Z_{thrpt}	Annual battery throughput
$R_{batt,f}$	Battery float life

1) Solar PV Mathematical Model

The mathematical model of solar PV for Solar PV is as in (1) – (3).

$$E_{PVG} = G(t) \times A \times P \times \eta_{PVG} \quad (1)$$

$$\eta_{pvg} = \eta_r \eta_{pc}[1 - \beta(T_C - T_{cref}) \quad (2)$$

$$T_C = T_a + \{\frac{NOCT-20}{800}\}G_t \quad (3)$$

2) Biomass Generator Mathematical Model

The Mathematical model of biomass generator is as in (4) and (5):

$$Electricity\ generation = \frac{Kcal\ x1.16}{1000} \quad (4)$$

The hourly energy output production by the biogas digester is evaluated as in (5):

$$E_{BGG(t)} = \frac{Biogas\ availability\ (m3/day)xCV_{BGG}x\ \eta_{BGG}\ x\Delta t}{860\ x\ h_{BGG}} \quad (5)$$

3) Mathematical Model of Inverter

The mathematical model of inverter is as in (6):

$$P_{in} = \frac{P_{ch}}{\eta_{in}} \quad (6)$$

4) Battery Mathematical Model

The mathematical model of battery (storage) is as in (7) and (8). The battery autonomy (A_{batt}) and battery lifetime (R_{batt}) will be calculated by HOMER based on (7) and (8) respectively:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} (1 - q_{min}/100)(24h/d)}{L_{prim,ave}(1000Wh/kWh)} \quad (7)$$

$$R_{batt} = \min\left\{\frac{X_{batt} Y_{lifetime} R_{batt,f}}{Z_{thrpt}}\right\} \quad (8)$$

III. RESULTS AND DISCUSSION

A. Optimization Result

The software was run several times after entering all of the input variables into the modeling tool to ensure that the results were feasible. 4,273 solutions were simulated, 3,565 of which were feasible. The optimization results are shown in Table III. The optimal configuration is the PV-BG-BB hybrid system. The Levelized COE is $0.178/ kWh, with RF of

100%. This means that nearly all of the energy used by the hybrid system to meet the load is generated from renewable sources. Ten Hybrid Power Systems were found to be technically feasible as power generation options for Kajola village.as shown in Fig. 7. This means that all hybrid topologies can satisfy Kajola's energy needs. However, each has unique characteristics such as NPC, COE, Emissions, RF, capacity shortages, and unmet load. This configuration is a good choice for implementation because the hybrid power system is entirely reliant on renewable energy.

1) Solar PV Output

The rated capacity of PV module is 11.2 kW. The mean output is 32,980 kW and the capacity factor is 14.6 %. The total energy production is 39.3 kWh/year. Hours of operation are 4,380 hours and levelized COE of $0.0805/kWh. Solar PV output is displayed as in Fig. 8. Electricity generation is higher during dry season when solar radiation and clearance index are high.

2) Biomass Generator Output

The annual average biomass resource for Kajola is 6.06 t/day. Fig. 9 depicts the hybrid system's generator power output. Generator power production was limited due to the generator power distribution. The total number of hours worked per year was 8,007, which is less than half an hour per day. This hybrid power system's generator produced a mean power output of 11.3 kW, a minimum electrical output of 6.25 kW, and a maximum electrical output of 25 kW. As shown in Figure 8, the amount of biogas fuel consumed per year is approximately 44.8 tons. The electricity production by each of the individual power hybrid system unit shows that biomass resources account for 90,787 kWh, representing 86.4 percent of total electricity production of the HPS. In the HPS, electricity is generated primarily from biomass sources.

3) Monthly Average Electric Production of the Optimal Configuration

The best choice is guided by economic considerations. As a result, the PV-BG-BB hybrid system meets the economic criteria and constraints, with PV accounting for 13.6% of total energy generation and the biogas generator accounting for 86.4 percent of total energy generation in the HPS. The results showed that PV power is available 4380 hours per year, or approximately 12 hours per day. When the solar radiation is at its peak, the mean output is 1.64 kW and the maximum output is 8.62 kW. The total energy production per year is 214,331 kWh. The percentage of energy production of the main energy sources of the hybrid system is as in Fig. 10. The results showed that the energy need for Kajola can be met sustainably by the renewable resources, with no need of diesel generator penetration.

B. Economic Metric and Simple Payback Period

A positive Return on Investment (ROI) indicates that the net returns are favorable because total returns are more than total costs. A negative ROI indicates that the net returns are failing (that is, this investment is losing money) because total costs exceed total returns. Table III shows a positive ROI of 328.6 percent, indicating that the hybrid project is highly profitable. The simple payback period is 0.33 year. Table III shows a positive value for the present cost, which is the difference between the winning hybrid system and the net present costs of the base case system. The hybrid power project is both viable and profitable.

TABLE III: ECONOMIC METRIC OF THE SYSTEM ARCHITECTURE

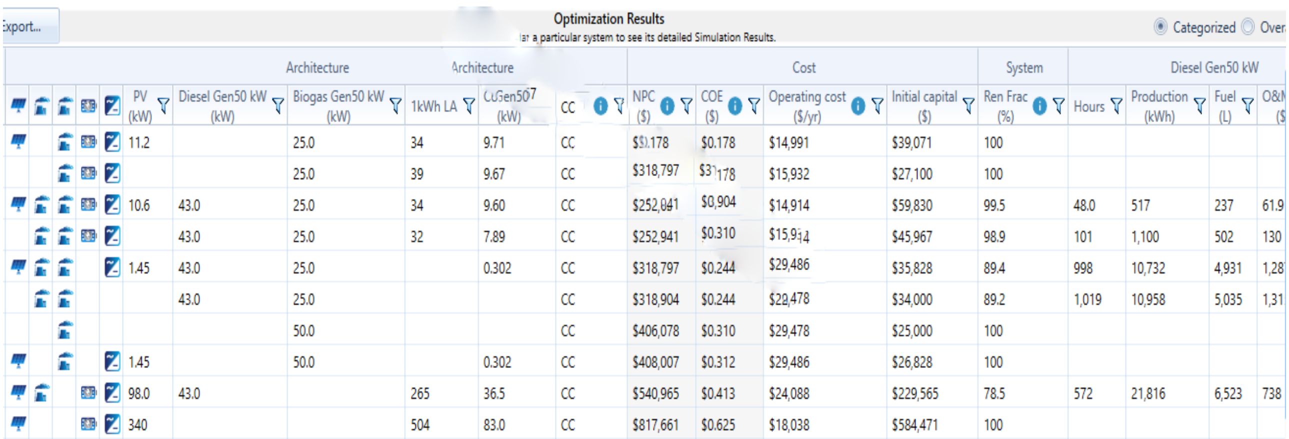
Pollutant Emissions	Value (kg/year)
Carbon dioxide	81
Carbon monoxide	0.733
Unburned hydrocarbons	0.0323
Particulate matter	0.00439
Nitrogen oxides	0.689

C. Emission Analysis of the Hybrid System

The emission analysis from the optimal hybrid system is as shown in Table IV. There is almost no detrimental emission to the environment. The hybrid option is feasible because the renewable fraction is 100 percent, implying that all energy production is derived from renewable sources. The results showed that biomass and solar resources alone are capable of meeting Kajola village load demand in a sustainable manner. The hybrid system is good for the environment.

TABLE IV: EMISSION OF THE OPTIMIZED HPS CONFIGURATION IN KAJOLA VILLAGE

Metric	Value
Present Worth ($)	$739,475
Annual Worth ($/Yr)	$57,202
Return on Investment (%)	328.6
Internal Rate of Return (%)	315.3
Simple Payback (Yr)	0.33
Discounted Payback (Yr)	0.35



Architecture						Cost				System	Diesel Gen50 kW			
PV (kW)	Diesel Gen50 kW (kW)	Biogas Gen50 kW (kW)	1kWh LA	CuGen507 (kW)	CC	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Hours	Production (kWh)	Fuel (L)	O&M ($)
11.2		25.0	34	9.71	CC	$[illegible].178	$0.178	$14,991	$39,071	100				
		25.0	39	9.67	CC	$318,797	$3[illegible]178	$15,932	$27,100	100				
10.6	43.0	25.0	34	9.60	CC	$252,841	$0.904	$14,914	$59,830	99.5	48.0	517	237	61.9
	43.0	25.0	32	7.89	CC	$252,941	$0.310	$15,914	$45,967	98.9	101	1,100	502	130
1.45	43.0	25.0		0.302	CC	$318,797	$0.244	$29,486	$35,828	89.4	998	10,732	4,931	1,28
	43.0	25.0			CC	$318,904	$0.244	$29,478	$34,000	89.2	1,019	10,958	5,035	1,31
		50.0			CC	$406,078	$0.310	$29,478	$25,000	100				
1.45		50.0		0.302	CC	$408,007	$0.312	$29,486	$26,828	100				
98.0	43.0		265	36.5	CC	$540,965	$0.413	$24,088	$229,565	78.5	572	21,816	6,523	738
340			504	83.0	CC	$817,661	$0.625	$18,038	$584,471	100				

Fig. 7. Optimization result.

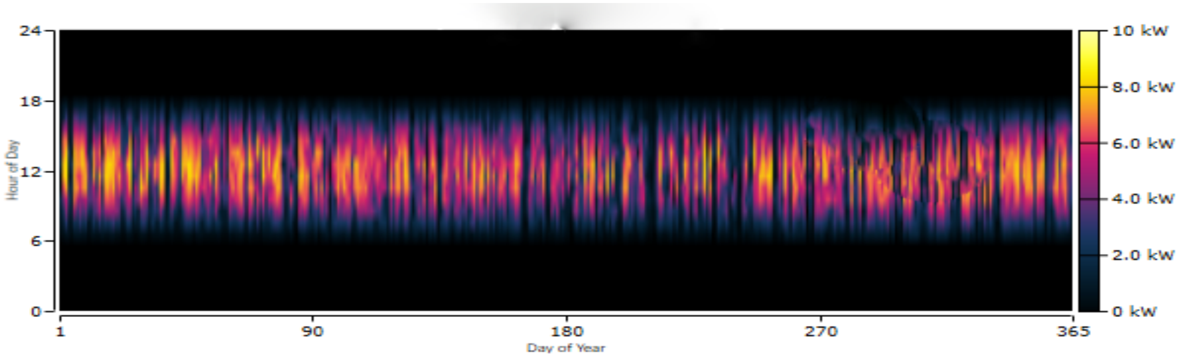


Fig. 8. Monthly solar PV output of the system.

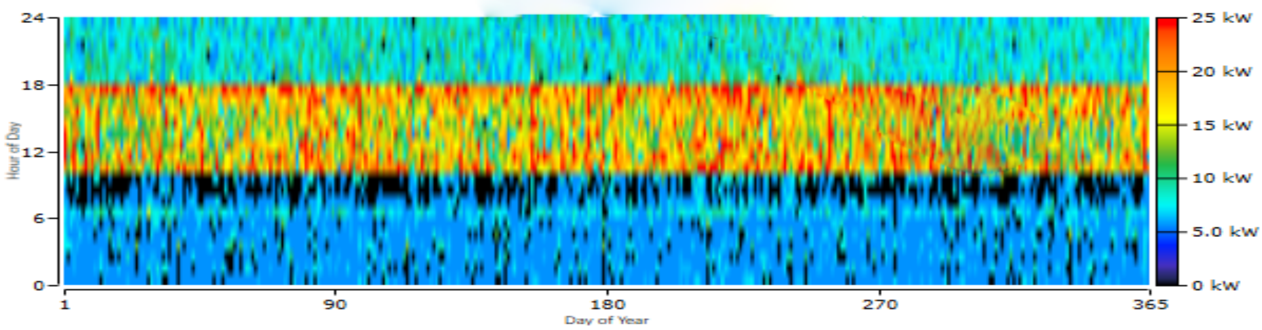


Fig. 9. Biomass generator output.

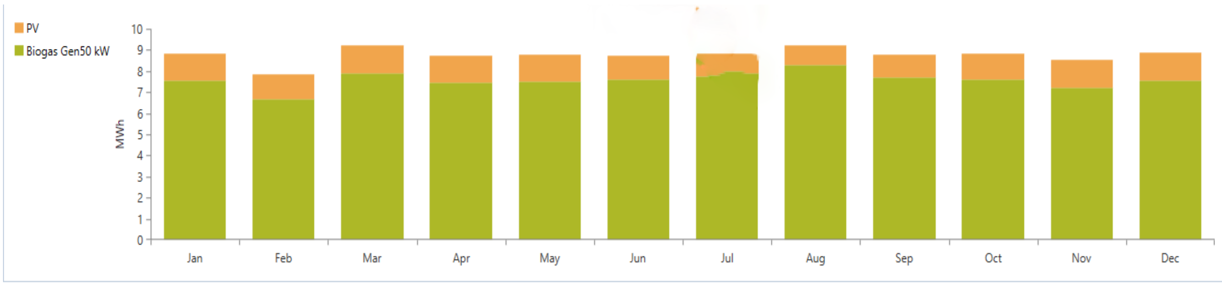


Fig. 10. Monthly average electric production.

IV. Conclusion

The feasibility and techno-economic analysis of off-grid Solar Photovoltaic (PV) /Biomass/Diesel /Battery hybrid system for a rural village-Kajola, Nigeria was conducted in this work. Six Hybrid Power Systems were found to be technically feasible as power generation options for Kajola village. This means that all hybrid topologies can satisfy Kajola's energy needs. However, each has unique characteristics such as NPC, COE, Emissions, RF, capacity shortages, and unmet load. The results revealed that PV-BG-BB hybrid system is the optimal configuration. This configuration is a good choice for implementation because the hybrid power system is entirely reliant on renewable energy. The investment is worthwhile for Kajola village.

The system is feasible with a minimum NPC of $232,863 and a minimum COE of $0.178 kWh. The high percent ROI and simple payback period, the economic metric indicates that the project would be a good investment opportunity. Although the initial cost is high, the ROI is 328.6 percent, which is exponentially high and favors investment. The breakeven period is also less than a year, when investors begin to profit from their investment. Even though, it is cheaper and economical to connect from the grid, hybrid power system still remains the best configuration for rural electrification especially in places where extension through the grid is geographically and economically infeasible.

Appendix

Components costing of the proposed Hybrid System [a]

A	Biogas Generator	AC
1	Capacity	25 kW
2	Capital Cost	$12,500
3	Replacement Cost	$83,107
4	Operation and Maintenance Cost (O &M)	$77,633
5	Life time	14,973 hours
B	Solar PV array	DC
1	Capacity	11.2 kW
2	Capital Cost	$13,457
3	Replacement Cost	$0
4	Operation and Maintenance Cost (O &M)	$1,450
5	Life time	25years
C	Battery	
1	Capacity	34 kWh
2	Capital Cost	$10,200
3	Replacement Cost	$9,313.61
4	Operation and Maintenance Cost (O &M)	$4,395.36
5	Minimum Life time	9.58 years
6	Initial state of charge	100%
D	Converter	
1	Capacity/Size	9.71 kW
2	Capital Cost	$2,913.89
3	Replacement Cost	$1,236.29
4	Operation and Maintenance Cost (O &M)	$0
5	Life time	15 years
6	Inverter efficiency	90%
7	Rectifier input	85%

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