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DESIGN AND SIMULATION OF A HYBRID BIOMASS-SOLAR RENEWABLE ENERGY SYSTEM FOR RURAL DWELLERS IN NIGERIA

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ABSTRACT

This paper aims at designing a stand-alone hybrid power plant which uses solar and biomass renewable energy systems to produce electricity that can be used to power rural areas in Nigeria. The location selected for the study is Unwana community in Ebonyi state which is in South-East geo-political zone of Nigeria. The location is estimated to have a total of one hundred households, eight shops, one public primary/secondary school, one community hall, one community health center, community water project, street lights and miscellaneous load. The average daily demand for the location is estimated to be 240.1 kWh/day with a peak demand of 41.6 kW. The location has an annual solar irradiance of 4.71kWh/m^2/day and a yearly average temperature of 24.91°C. The biomass feedstock used for the study is rice husk. A daily average of 1.5 metric tons of rice husk is obtainable in the location. HOMER Pro software was used to design, simulate and optimize for the best hybrid system combination to satisfy the demand of the location given the available resources. The system with the lowest Net Present Cost consist of one 20kW biogas generator, one 10kW biogas generator, 4.6kW PV panels, 31 strings of 12V, 1kWh lead acid battery and 8.65kW converter. 6.3% of the total power is derived from solar and the remaining 93.7% from biomass.

KEYWORDS: Renewable Energy, Rural Electrification, Biomass, Solar, Hybrid, HOMER Pro.

1. INTRODUCTION

1.2 billion people out of the total 7.6 billion world population lacks electricity (International Energy Agency, 2016). About 585 million people, which correspond to about 49% of the world population without access to electricity are from the sub-Saharan Africa, most of which dwell in the rural areas of these countries.

Nigeria, records a population of over 82 million people out of its total population of about 187 million people with no access to electricity supply (Central Intelligence Agency, 2016). Approximately only 45% of its entire population is connected to the national grid and most of the people with access to grid electricity in the country are found in the urban areas thus leaving citizens in the rural areas with little or no access to electricity supply. This initiated the Rural Electrification Program by the Rural Electrification Agency of Nigeria in 2005 (National Council on Power, 2014). The program aims at providing reliable electricity to 75% of the population in the rural areas by the year 2020 with at least 20% renewable energy mix since grid extension alone will not be sufficient.

Other studies have been carried out on the potentials of renewable energy in Nigeria. Ohunakin et al., 2014 carried out a detail feasibility study on solar energy applications and its development in Nigeria. Adaramola, 2014 carried out an economic analysis, combining 80kW solar PV and grid electricity at a solar PV cost of $2400/kW at an average solar irradiance of 6.0kW/h/m2/day. The study showed viability in north-eastern part of Nigeria. Olatomiwa et al., 2015 carried out an economic evaluation for hybrid energy systems covering six geo-political zones in Nigeria for rural electrification. The study applied a hybrid of solar PV, wind and diesel system. Nigeria also has other energy sources that can meet its demand if well harnessed. This paper focuses on the use of two of these renewable energy resources namely biomass and solar.

2. MATERIALS AND METHODS

Materials used for the design and simulation include a laptop computer, HOMER Pro software version 3.11, PVsyst software version 6.6.7, Microsoft office tools and Adobe creative suite. The methods involved collation of data required for the design and simulation of the hybrid renewable energy system. The data collated include the amount of renewable energy resources around the study location and the load profile of the study location. The design and simulation of the system was carried out after the data collation with HOMER Pro software.

2.1 Renewable Energy Resource Data

This section shows renewable energy resource data collated for the study location (Unwana community). Table 1 shows coordinates and the climate type of the study location.

Table 1: Location coordinates and climate type of the Unwana community.

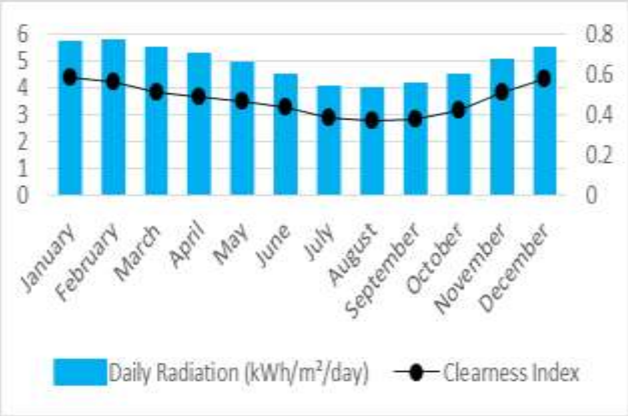
Study location	Geo-political zone	Coordinates	Climate type
Unwana (Ebonyi state)	South-East	5.524°N/7.567°E	Tropical Savannah.

2.1.1 Solar Resources

Table 2 shows the average monthly irradiance, clearance index and temperature of Unwana community as downloaded from NASA database using the coordinates. Figure 1 gives the charts representing the data in table 2.

Table 2: Average monthly irradiance, clearance index and temperature of the study location.

Month	Daily radiation (kWh/m^2/day)	Clearness index	Temperature(℃)
January	5.530	0.588	25.350
February	5.590	0.562	25.760
March	5.532	0.512	25.680
April	5.090	0.488	25.770
May	4.720	0.466	25.650
June	4.310	0.435	24.770
July	3.850	0.386	24.050
August	3.770	0.368	23.940
September	3.940	0.381	24.150
October	4.270	0.426	24.450
November	4.840	0.510	24.680
December	5.290	0.576	24.710
Average	4.71	0.476	24.91



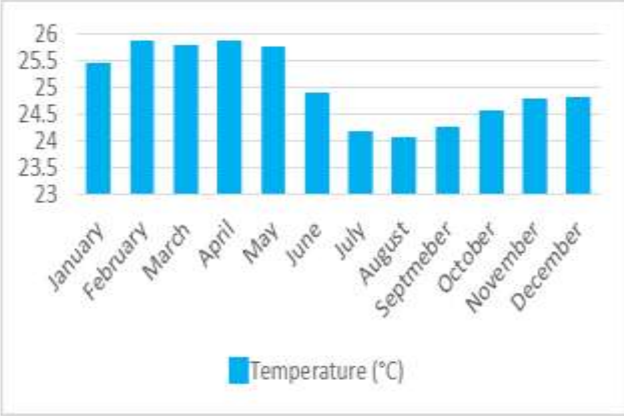


Fig. 1: Charts of daily radiation, clearance index and temperature of the location.

The following equation defines the clearness index:

$$K_T = \frac{H_{ave}}{H_{o,ave}} \qquad \ldots\ldots(1)$$

Where H_{ave} is the monthly average radiation on the horizontal surface of the earth in (kWh/m^2/day) and $H_{o,ave}$ is the extraterrestrial horizontal radiation, meaning the radiation on a horizontal surface at the top of the earth's atmosphere (kWh/m^2/day).

2.1.2 Biomass Resource

The major biomass feedstock material that is derivable from the location's environs is rice husk and rice straw which are residues of rice processing. Ebonyi state, being the fifth largest rice producing state in Nigeria produces approximately 19000 metric tons of rice paddy per annum (The Eagle Online, 2016). From a field survey, an average of 1.5 metric tons of rice husk can be supplied daily to any site at Unwana from the nearest rice mills at the cost of 20 000 naira (labour and transportation) which is equivalent to about $56 at the current exchange rate of 360 naira to one US dollar. This amounts to a fuel cost of approximately $37/ton.

Table 3 gives the data obtained from a proximate analysis done on rice husk in university de sains in Malaysia.

Table 3: Contents and calorific value of dried rice husk (Mohamad et al., 2008).

Fixed carbon (% dry basis)	Volatile matter (% dry basis)	Ash (% dry basis)	Moisture (% wet basis)	LHV MJ/kg (% dry basis)	Bulk density kg/m^3
13.49	62.95	18.15	10.40	14.80	91.46

2.2. Load Demand Assessment

The load is categorized into two types namely domestic and social infrastructural loads. For simplicity purpose, the domestic load will be labelled category A and the social infrastructure load will be labelled category B. The loads profile in this section represents an assumption based on customer classification and cluster method for the community. Table 4 gives a summary of the daily load demand of the location for a day in rainy season (March to October) and a day in dry season (November to February).

Table 4: Summary of the estimated load profile for the study location.

Load description	Number in use	Power rating (watts)	Power rating (Kw)	Total rating (kW)	Rainy season (March-October)		Dry season (November-February)	
					Hours/day	kWh/day	Hours/day	kWh/day
Category A: Domestic load								
Lighting(CFL)	4	18	0.018	0.072	7	0.504	7	0.504
Television	1	80	0.08	0.08	5	0.4	5	0.4
DVD player	1	20	0.02	0.02	2	0.04	2	0.04
Radio	1	10	0.01	0.01	8	0.08	8	0.08
Ceiling fan	2	30	0.03	0.06	20	1.2	10	0.6
Total for 100 households				**24.2**		**222.4**		**162.4**
Category B: Social infrastructure load								
Primary health center								
Lighting (CFL)	6	18	0.018	0.108	12	1.296	12	1.296
Refrigerator	1	480	0.48	0.48	14	6.72	12	5.76
Television	1	80	0.08	0.08	6	0.48	6	0.48
Ceiling fan	3	30	0.03	0.09	21	1.89	13	1.17
Total				**0.758**		**10.386**		**9.379**
Public primary/ secondary school								
Lighting (CFL)	8	18	0.018	0.144	0	0	0	0
Ceiling fan	3	30	0.03	0.09	5	0.45	2	0.18
Total				**0.234**		**0.45**		**0.18**
Community hall								
Lighting (CFL)	6	18	0.018	0.108	0	0	0	0
Television	1	80	0.08	0.08	8	0.64	8	0.64
Ceiling fan	4	30	0.03	0.12	9	1.08	6	0.72
Total				**0.308**		**1.72**		**1.36**
Market/shops								
Lighting (CFL)	8	18	0.018	0.144	3	0.432	3	0.432
Refrigerator	2	480	0.48	0.96	15	14.4	12	11.52
Ceiling fan	4	30	0.03	0.12	15	1.8	10	1.2
Total				**1.224**		**16.632**		**13.152**
Street lights								
LED light panel	40	30	0.03	1.2	11	13.2	11	13.2
Total				**1.2**		**13.2**		**13.2**
Community water project								
Water pumping machine (deferrable load)	2	1134	1.134	2.268	3	6.804	3	6.804
Total				**2.268**		**6.804**		**6.804**
Total consumption				**30.192**		**271.592**		**206.475**

2.3 Design and Simulation

The design was done with HOMER Pro version 3.11.2. The design aimed at selecting appropriate power generating and storage components that will utilize the available solar and biomass resources to meet the load demand. The components used include PV solar panels, batteries for storage, power converter, and biogas generators. A rundown of the components is given below.

2.3.1 Solar PV

For this design, a generic flat plate PV was used. HOMER Pro is used to optimize for the required capacity to be used. The details are given in the Table 5.

Table 5: Details of the solar PV.

Parameters	Value		Parameters	Value
Capital cost	\$3000/Kw		Efficiency	13%
Replacement cost	\$3000/Kw		Operating temperature	47°C
Operation/maintenance cost	\$10/year		Temperature coefficient	−0.5
Lifetime	25 years		Derating factor	80%

HOMER uses the following equation to calculate the output of the PV array for each time step:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \left[1 + \alpha_P (T_C - T_{C,STC})\right] \qquad \ldots\ldots(2)$$

Where Y_{PV} is the rated capacity of the PV array(kW), f_{PV} The PV derating factor(%), $\bar{G}_T$ is the solar radiation incident on the PV array(kW/m^2), $\bar{G}_{T,STC}$ is the incident radiation at standard test conditions(1kW/m^2), α_P is The temperature coefficient of power(%/°C), T_C is the PV cell temperature(°C) and $T_{C,STC}$ is the PV cell temperature under standard test conditions(25°C).

2.3.2 Biogas generators

In this design, two generic biogas generators were considered to be adequate for the system. Inputs ranging from 0 to 50kW was specified in the search space in order for HOMER Pro to optimize for the required sizing and most cost effective operating sequence. Table 6 gives the details of the selected biogas generators.

Table 6: Details of the biogas generators.

Parameters	Value		Parameters	Value
Capital cost	\$500/kW		Operation/maintenance cost	\$0.03/operating hour
Replacement cost	\$500/kW		Lifetime	20,000 hrs.

Fuel consumption of the biogas generator is determined by the fuel curve equation as follows:

$$F = F_0 Y_{gen} + F_1 P_{gen} \quad ......(3)$$

Where $F$is the fuel consumption, F_0 is the fuel curve intercept coefficient (kg/hr/kW$_{rated}$) defined as the no-load fuel consumption of the generator divided by its rated capacity, F_1 is the fuel curve slope (kg/hr/kW$_{output}$) defined as the marginal fuel consumption of the generator, Y_{gen} is the rated capacity of the generator (kW), P_{gen} is the electrical output of the generator (kW).

2.3.3 Battery

For energy a generic 12V, 1kWh lead acid battery was used in the design. The details of the selected storage battery are given in Table 7.

Table 7: details of the battery.

Parameters	Value	Parameters	Value
Capital cost	$300/kW	Maximum capacity	83.4Ah
Replacement cost	$300/kW	Roundtrip efficiency	80%
Operation/maintenance cost	$10/year	Maximum charging current	16.7A
Lifetime	10years	Maximum discharge current	24.3A
Nominal voltage	12V	Minimum state of charge	40%
Nominal capacity	1kWh		

The battery autonomy is calculated as follows:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left[\frac{1-q_{min}}{100}\right] (24h/d)}{L_{prim,ave}(1000Wh/kWh)} \quad ......(4)$$

Where A_{batt} is the storage bank autonomy (hr), N_{batt} is the number of batteries in the storage bank, V_{nom} is nominal voltage of a single storage (V), Q_{nom} is the nominal capacity of a single storage (Ah), q_{min} is the minimum state of charge of the storage bank (%) and $L_{prim,ave}$ is the average primary load (kWh/d).

2.3.4 Converter

The parameters of the converter are given in Table 8.

Table 8: Details of the converter.

Parameters	Value	Parameters	Value
Capital cost	$300/kW	Lifetime	15years
Replacement cost	$300/kW	Inverter efficiency	95%
Operation/maintenance cost	$0	Rectifier efficiency	90%

2.3.5 Economics and constraint

The economic inputs for this design include annual inflation rate and annual interest rate which was gotten from the Central Bank of Nigeria. The economics and constraint inputs are given in table 9.

Table 9: Economic and constraint inputs.

Economics	Value	Constraints	Value
Nominal discount rate	14%	Maximum annual capacity shortage	0%
Expected inflation rate	12.5%	Minimum renewable fraction	50%
Project lifetime	25 years	Operating reserve	10% of load

The resulting schematic of the hybrid plant after adding all the required components is shown in the Fig. 2.

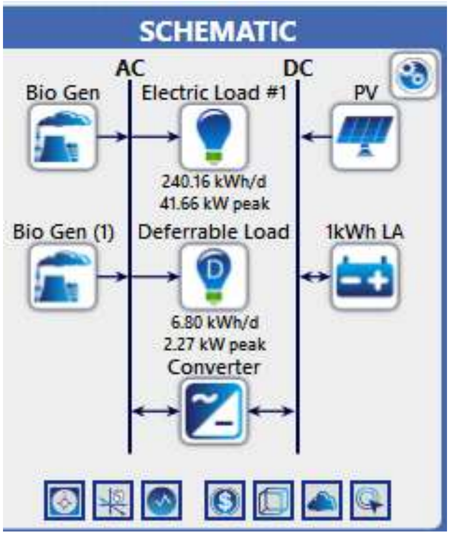
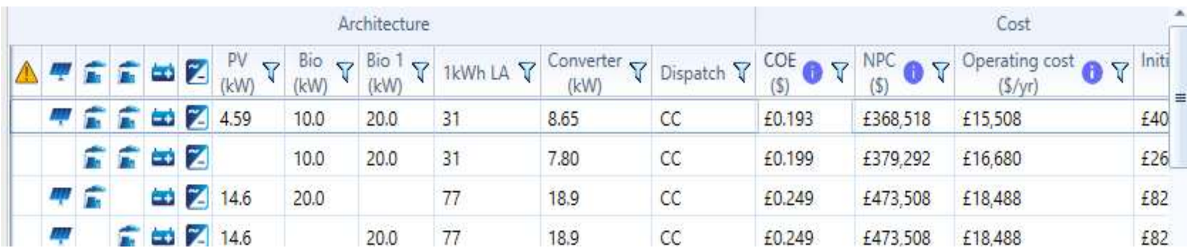


Fig. 2: Schematic of the hybrid biomass-solar plant.

3. RESULTS AND DISCUSSIONS

Fig. 3 shows the optimization results from the simulation. In the result, different feasible configurations of the system are given and arranged according to their net present cost, from the least to the highest. The result having the least net present cost is considered the most feasible. The architecture of the system with the least net present cost is given in Table 10.



Architecture						Cost			
PV (kW)	Bio (kW)	Bio 1 (kW)	1kWh LA	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initi
4.59	10.0	20.0	31	8.65	CC	£0.193	£368,518	£15,508	£40
	10.0	20.0	31	7.80	CC	£0.199	£379,292	£16,680	£26
14.6	20.0		77	18.9	CC	£0.249	£473,508	£18,488	£82
14.6		20.0	77	18.9	CC	£0.249	£473,508	£18,488	£82

Fig. 3: The optimization result.

Table 10: The system architecture components and capacities.

Component	Capacity	Component	Capacity
Biogas Generating set 1	20 kW	12V 1kWh lead acid battery	31 strings in parallel
Biogas Generating set 2	10 kW	System converter	8.65 kW
Flat plate PV	4.59 kW		

3.1 Cost Summary

Fig. 4 shows a summary of the costs of the individual system components and the total net present cost. From the figure, it can be seen that the PV plate has the highest capital cost but the least running cost while the biogas generators have high running cost due to fuel cost. The total net present cost has a Naira equivalent of 132,666,343 (one hundred and thirty-two million, six hundred and sixty-six thousand, three hundred and forty-three Naira).

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Lead Acid	£9,300.00	£15,281.98	£6,553.91	£0.00	-£3,339.22	£27,796.68
Generic Biogas Genset	£5,000.00	£24,890.56	£30,780.13	£92,515.81	-£3,352.68	£149,833.82
Generic Biogas Genset (1)	£10,000.00	£24,885.98	£35,391.12	£105,451.35	-£3,680.32	£172,048.13
Generic flat plate PV	£13,766.91	£0.00	£970.18	£0.00	£0.00	£14,737.10
System Converter	£2,595.41	£2,127.75	£0.00	£0.00	-£621.27	£4,101.90
System	£40,662.33	£67,186.27	£73,695.35	£197,967.16	-£10,993.49	£368,517.62

Fig. 4: Cost summary of the system.

3.2 Electrical Summary

Fig. 5 shows the proportions of power generated by the generating components. Table 11 is a summary containing data from the chart. From the table, the biogas genset 2 which is the 20kW generator produces the highest power which corresponds to 49.9% of the total production.

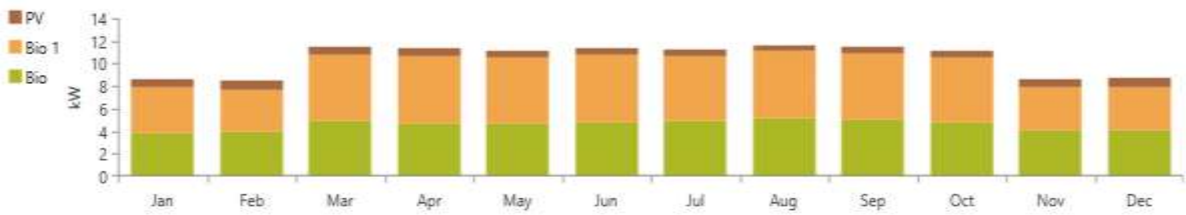


Fig. 5: Chart of generating proportions of the bio generators and PV system.

Table 11: Electrical summary of the hybrid plant.

Component	Production (kWh/year)	%
Flat plate PV	5,771	6.30
Biogas genset (10kW)	40,151	43.8
Biogas genset (20kW)	45,740	49.9
Total	91,663	100

3.3 Fuel consumption summary

The yearly available quantity of fuel that is obtainable in the study location is approximately 548 tons (daily average of 1.5 tons, times 365 days). This exceeds the total feedstock consumed in a year as seen from Table 12 (253 tons).

Table 12: fuel summary of the hybrid plant.

Quantity	Value	Units
Biogas genset (10kW)	118	tons/yr
Biogas genset (20kW)	135	tons/yr
Total feedstock consumed yearly	253	tons/yr
Average feedstock per day	0.693	tons/day
Average feedstock per hour	0.0289	tons/hr

4. CONCLUSION

In this paper a hybrid biomass-solar renewable energy system has been designed and simulated for rural settlements in Nigeria using Unwana community as a case study location. The results show that it is feasible to meet the electricity demands of this study location using this designed system given the available biomass and solar resources. The most economic configuration of the plant is shown to have 93.7% of the total electricity produced from biomass (sum of the 43.8% and the 49.9% produced by the 10kW and 20kW biogas generators respectively) and the remaining 6.3% derived from solar. Further studies will be conducted to compare the economics between generating with this renewable energy system and conventional means of generation with grid extension in order to determine if the system is cost effective.

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