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Exploring Technically Feasible and Economically Viable Hybrid Renewable Energy Solution for Off-Grid Electricity Supply

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ABSTRACT: *Solar energy as one of the many sources of renewable energy-based off-grid electricity supply is traditionally considered as an expensive and unreliable source of power. But as technology improves over the years, renewable energy sources are beginning to take the stage of modern energy divide. Based on the limited generation and distribution companies (GENCOs and DISCOs) grid electricity supply in Nigeria, it becomes pertinent to complement available grid power with renewable sources. The purpose of this study is to propose the best hybrid technology combination for electricity generation to reliably satisfy the electrical needs of an off-grid remote village, Ofubu, New Patani in Bayelsa State, Nigeria. Solar PV systems and diesel generator are considered. The study estimates the day-to-day load demand Using HOMER software. Identification of the optimal off-grid option and comparison with conventional grid extension was carried out. The results obtained shows that hybrid combination of an PV-diesel is an effective alternative for an off-grid rural location and it is sustainable, techno-economically viable and environmentally friendly most especially considering the concept of green and clean energy source. The study also discussed issues that are likely to influence the realization of the optimal solution.*

I. Introduction

Nigeria, a nation of over 180 million people on the African continent, endowed with both natural and human resources, lacks the capacity to generate electricity which is the bedrock of every developed civilization. Nigeria is endowed with vast oil and gas reserves and also abundance of renewable energy potentials. For many years the country has been facing energy crisis that is hampering its economic development, which has a major impact on its ability to reduce poverty and achieve Millennium Development Goals (MDGs). Despite her huge natural resources, it is still one of the poorest countries in the world with an estimated gross domestic product (GDP) per capita of $2,758 (nominal) (IMF, 2016). An estimated 60-70% of its population does not have access to electricity and without it, civilization is but a primitive existence. At present only 10 % of rural households and 30- 40% of the country's total population has access to electricity (Sambo, 2006). Energy is one of the key fundamentals for economic development and all human activities in this era. The energy sector in the country totally rely on government partially subsidized fuel and funding of major energy plants and energy capital projects by the federal states and governments and its agencies.

Perhaps it is only individuals that are neither living nor doing business in Nigeria that does not know that lack of adequate energy supply especially electricity, is the major challenge the country is facing to fully utilize its economic potentials in other to achieve economic development. This is also the most significant factor which is affecting the country's race to be one of the biggest and top twenty economies of the world by 2020. The issue of how to find lasting and permanent solutions to the problems has remained a priority of every successive government in the last sixteen (16) years. The Nigerian government has not been able to find permanent solutions that will resolve the problems due to the adaptation of short term, hasty policies and also still undergo energy projects which are detrimental to long-term energy policies that will not help the nation to achieve sustainable and efficient energy utilization. For example, what the country has done is still usage of various alternatives that are still within the limits of fossil fuels, which are the only source that currently powers the nation economy (Suleiman, 2010).

Knowing the potentials of exploiting solar energy source to meet Nigeria electricity demand is a major challenge. This will involve determination of economic, social and geographic factors affecting the use and growth of solar renewable energy sources (SRES) as well as technical requirements to run solar source of energy in Nigeria. The aim of this paper is to investigate the potentials of exploiting solar renewable energy source for electricity generation in Nigeria. The objectives are to:

- Investigate the potentials of generating electricity in Nigeria using solar energy Global Horizontal Irradiance (GHI) from various geographical locations in Nigeria, with a case study of Ofubu village, New Patani, Bayelsa state.
- Harness solar renewable energy for electricity generation to support the limited power generated in Nigeria using HOMER Software.
- Design robust hybrid SRES model in Nigeria

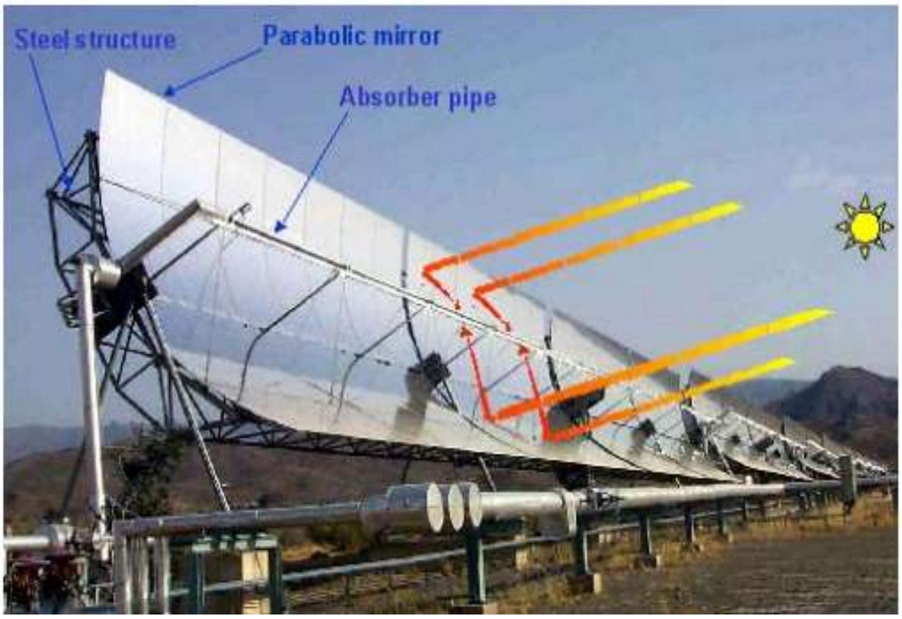
This will eventually close the gap of 60-70% that does not have access to environmentally friendly electrical energy.

Definition of Key Words
Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DIF).

II. Literature Review

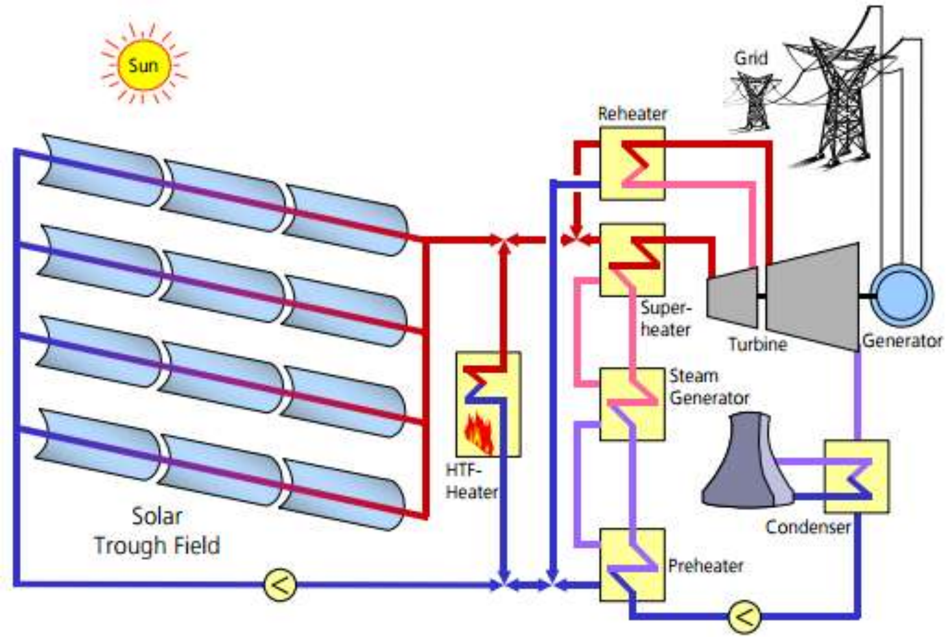
Day by day, the sun radiates enormous amount of energy. In a day, it radiates so much energy than the world uses in a year. The sun energy travels at the speed of light of $3.0x10^8$ m/s through a distance of 93,000 miles to reach the earth (NEED, 2016). This energy is renewable, hence one wonders why after all these centuries of human existence- the sun's energy have remained at the background of energy generation divide. Lately, Nigeria has started looking at the potential of using solar energy to produce electricity. As the day goes by manyNigerians are begin to look at the prospect of generating unlimited energy for daily use, considering the fact that the government electricityinfrastructuresare not reliable and sufficient to provide electricity for its citizens.

There is more than enough solar energy to harness in Nigeria and other parts of the world with sufficient sunlight. On the average 1,700 kWh can be generated from a square meter of land exposed to sunlight every year (Hoffmann and Teske, 2006). Solar Electricity can be generated from two main methods: Solar Thermal Power Plant (STPP) and Photovoltaic (PV) .STPP harnesses heat from the sun; this heat is collected and used for the generation of electricity. The world can be supplied with electricity conveniently from one percent of the surface of the Sahara desert using solar power plant, making solar plant possible mostly around the sun-belt (Quaschning and Muriel, 2001). There are various types of solar plants, amongst them, the most widely used are the parabolic trough and solar power tower. The parabolic trough power plants are made up of cylindrical parabolic mirror that focus the sunlight to concentrate the heat as shown in figure 1.0



*(*Source: "*Solar Power – Photovoltaics or Solar Thermal Power Plants?" Oct2001)*
Figure 1: Principle of parabolic trough solar collector

Many of these collectors of about a hundred meters long rows are installed and arranged such that, the mirrors concentrate the sunlight on a metal absorber pipe more than 80 times in the line of focus to give the required energy, to run the plant.



*(*Source: "*Solar Power – Photovoltaic or Solar Thermal Power Plants?", October 2001)*

Figure 2: Principle of parabolic trough solar power plant

STPP systems have an advantage over PV because it is relatively easier to store thermal energy compared to electrical energy storage (Ekins-Daukes, 2009). Areas in with high sunshine like in the three Northern Geopolitical regions in Nigeria can harness the CST technology conveniently to generate electricity.

A single PV cell is made up of silicon semiconductor, with two layers; one positively charged and the other negatively charged. These two layers allow DC current to flow through when there is sunlight. The greater the light intensity, the higher the flow of electricity. However, this does not mean the brightness of sunlight because sometimes a slight cloudy weather can give rise to a higher energy yield than a cloudless sky due to the reflection of sunlight by the slight clouds (Hoffmann and Teske, 2006).

Electricity generated through solar PV is really different from that of the solar thermal system which utilizes the sun rays to produce heat. Some advantages of PV solar power are:

a. Free fuel from the sun
b. Noiseless, no harmful emission or pollution
c. No moving part to cause wear and tear,
d. Less maintenance and low operational cost
e. Modular system that can be quickly installed

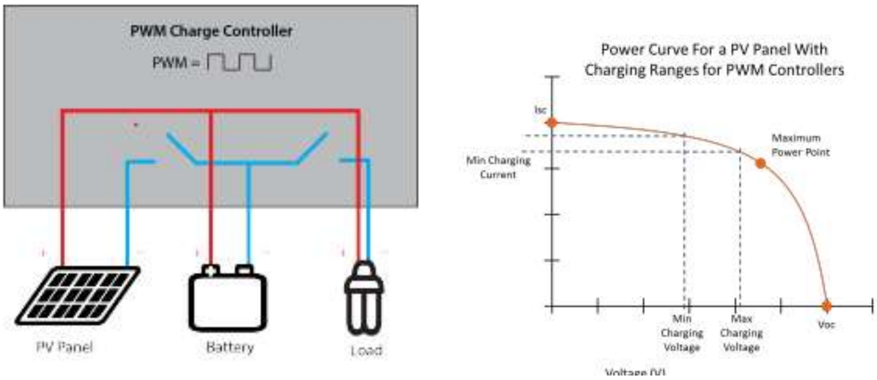
PV cells are not made in Nigeria presently but are imported from countries like China, UK, Japan, etc. Most PV cells are made from crystalline silicon which is sliced from ingot or castings or from grown ribbon or Thin Films deposited on a low-cost backing. The crystalline Silicon is the most widely used for PV modules because it uses the same technology developed by the electronics industry. However, the efficiency of 20% is possible as demonstrated in the laboratory. Wafers, which are thin slices of silicon, are the basis for crystalline solar cells. While Thin Film modules are constructed by depositing extremely thin layers of photosensitive materials on low-cost material backing like glass, polymer foil or stainless steel (Hoffmann and Teske, 2006). Other cell types include concentrator cells, which focus the light onto a small area with Fresnel lens but cannot use diffused light and the Speral Solar Technology, that uses silicon bids bonded on aluminum foil matrix that give a substantial cost advantage. PV cells are soldered together under a sheet of glass to form modules that are portable, robust, waterproof and reliable for the production of the power output of 80% of the nominal power even after 20-25years. The most common PV-technologies these days are the single-crystalline silicon and the multi-crystalline silicon module(s) (Kjaer, Pedersen and Blaabjerb, 2002). Figure 3 shows a PV array.

Source: ("Energy savings Engineering" http://www.energysavingsengineering.com, March, 2017)

Figure 3: Solar PV array

The PV systems generate DC current which can be used to run small DC equipment, but to provide power for homes and communities in Nigeria- the voltage produced by the PV modules must be converted to 240V AC or more volts through the inverter. It converts DC produced by a DC source to AC and when a rectifier is attached, it is referred to as a converter. However, a good inverter/converter should perform at least two functions in PV system. First, the low DC voltage generated by the PV module must be amplified to a high AC voltage level into the Stand-alone (off-grid), National grid or Micro-grid. Since the power delivered from the PV module is very sensitive to the point of operation, there should be a function in the inverter/converter for tracking the Maximum Power Point (MPP) (Kjaer, Pedersen and Blaabjerb, 2002). For stand-alone (off-grid) PV system, rechargeable deep cycle batteries are used mostly to store energy for future use when there is no sunlight or at night. They are designed for solar application with battery lifetime of up to 15 years. However, the management of battery and the user's behavior determine the lifetime of the battery. Deep cycle batteries are mostly used in solar power applications; the battery connected to the PV array through a charge controller which protects the battery from overcharging and discharging, and can also provide information about the state of the system. If AC output is need when there is no sunlight or at night the inverter uses the DC power from the battery to function efficiently without interruption. If the system is hybrid, then the converter uses alternative sources to charge the battery when there are shortfalls of PV power (Rohit, 2013).

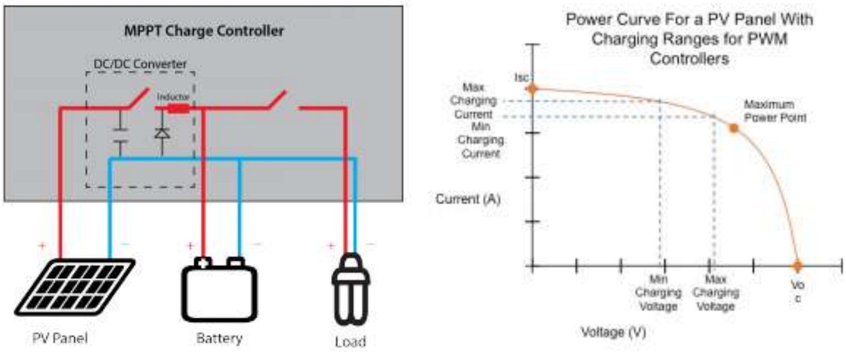
Charge controllers are very important for any PV system since PV output voltage and current varies with weather condition. It is, therefore, necessary to regulate and control the power required to charge battery bank of PV system. Charge controllers basically prevent overcharging of the batteries connected to the PV System and protecting the PV modules. There are two types of PV charge controllers: PWM (Pulse Width Modulation) Controller and MPPT (Maximum Power Point Tracking) Controller. During battery charging, PWM controller allows sufficient current as much as PV panel/array can give until it reaches the target set charge voltage, then the PWM controller senses and switches the charging current off/on to regulate and maintain the battery voltage by preventing overcharging and protecting PV cells. This quick switching is referred to as Pulse Width Modulation (PWM). It's cheaper and last longer because it has fewer electronics component compared the MPPT charge controller (Phocos, 2015). This controller operates in a region close to maximum power point but slightly higher as shown in Figure 4 below:



(Source: "*Comparing PWM & MPPT Charge Controllers*", *2015)*

Figure 4: PWM Charge Controller and PWM Power Curve

The MPPT charge control is 2 to 3 times more expensive that the PWM charge controller because it contains more electronics component and is able to track the maximum power from the PV panels /array by using the 'current' and 'voltage' parameter to acquire the optimum power (Watt = V x I) at any given time to charge the battery bank in a PV system. The indirect connection includes a DC/DC voltage converter that converts excess PV voltage to extra current at a lower voltage without any loss in power. MPPT has the special algorithm that tracks the maximum power point and adjusts the incoming voltage to retain maximum power during charging as shown in the curve and diagram in Figure 5 below:



(Source: "*Comparing PWM & MPPT Charge Controllers", 2015)*

Figure 5: MPPT Charge Controller and MPPT Power Curve

The total solar radiation on a horizontal surface is called Global Horizontal Irradiance (GHI). Photovoltaic systems output is a function of terrestrial solar irradiance (TSI) which is a measure of the power of the sunlight (W/m^2) This gives information of the general maximum output of solar PV system in a given time and location. TSI is a function of water vapor, solar elevation angle, aerosol concentration, site altitude and other atmospheric conditions. It should be noted that clouds do not decrease the irradiance by a fixed amount in W/m^2; rather it attenuate the sunlight by a given percentage for that cloud type. All extra TSI does not reach the ground on a clear sunny day. However, about 25% of the solar irradiance coming from the sun are absorbed and scattered as it passes through the atmosphere to reach the ground (Reno, Hansen and Stein, 2012).The Global Horizontal Irradiance (GHI) is the sum of the two types of irradiance; the Direct Normal Irradiance (DNI) and the Diffuse taking cognizance of the solar zenith angle, z as shown in equation 1.0

GHI = Diffuse + DNI x Cos (z) **(1)**

where z is the solar zenith angle

The measure of flux of solar beam radiation to a plane perpendicular to the sun's direction is referred to as DNI, which is the direct irradiance or beam irradiance. While the diffuse irradiance includes sunlight that is scattered all over and reflections from the earth surface, which depends on the surface. DNI is measured with pyranometer while Diffuse can be measured with pyranometer that is shaded from beam irradiance. GHI is measured basically with a pyranometer (Reno, Hansen and Stein, 2012). Figure 6 is the Solar Global Irradiation on the map of Nigeria:

(Source: "Soda -solar radiation data, Available at http://www.soda-pro.com/maps", February 2017).

Figure 6: Yearly Average of Daily Sums of Global Horizontal Irradiation of Nigeria

III. Electricity Demand In Nigeria

Electricity demand in Nigeria has increased over the years with increase in population. Though there has been some transformation in power generation in the country, it still cannot meet the daily electricity demand of Nigerians. Presently, the source of power supply is a mix of different energy sources. Thermal is the major source of energy used by Power Generating Companies (GENCOs) to generate electricity due to the huge reservoir of oil and natural gas available in Nigeria. Gas constitutes 71% of the electricity generated, oil constitutes 11%, and hydropower constitutes 18% tied into the national grid (pwc, 2016). Currently, the installed electricity power capacity is 6000MW. As at 2015, transmission network installed is 6000km of 132kV lines and 5000km of 330kV lines. These transmission network channels are overloaded with low capacity hovering around 2900MW-4000MW (Omorogiuwa and Okpo, 2015). Nigeria per capita power consumption is only 151KWh as compared to South Africa with 2000 KWh, even when the population of South Africa is far lesser than Nigeria (pwc, 2016).

However, there are small-scale stand-alone solar PV, Wind and biomass off-grid renewable sources of electricity in Nigeria. These small scale renewables are implemented in off-grid rural areas by some states, local government, Niger Delta Development Commission (NDDC) projects or other organizations to run utilities like small scale portable water supply plants and streetlights. Most Urban dwellers in Nigeria use personal Solar PV systems mount on their roofs to compensate for the limited power supplied by Power Distribution Companies (DISCOs).

IV. Methodology

This study uses National Renewable Energy Laboratory (NREL) developed software called HOMER to design and analyze micro–power systems in a selected village. In the pre–Homer analysis, GHI data from NASA for six major cities in six geopolitical regions in Nigeria is analyzed. Ofubu, a village in New Patani, Sagbama Local Government Area, Bayelsa State, is used as a case study. It is located in the Niger Delta region; one of the six geopolitical regions in Nigeria. Detailed assessment of the village load, solar available resources, and site layout are conducted. Off grid – PV system is designed with capacity that can be integrated with micro-grid system when available. To optimize the system design, comparison of a wide range of equipment with different constraints and sensitivities are used. The analysis is based on the technical properties and life-cycle cost (LCC) of the system. This involves Initial capital cost, installation cost, and running or operation cost considering total life span of the design.

Optimization of various combinations of renewable sources is carried out in order to satisfy the given load demand using alternative technology options and availability of these sources. The best result is selected suited for the best configuration. Business related analysis is also performed to a limited extent. Figure 7.0 shows flow diagram of the study

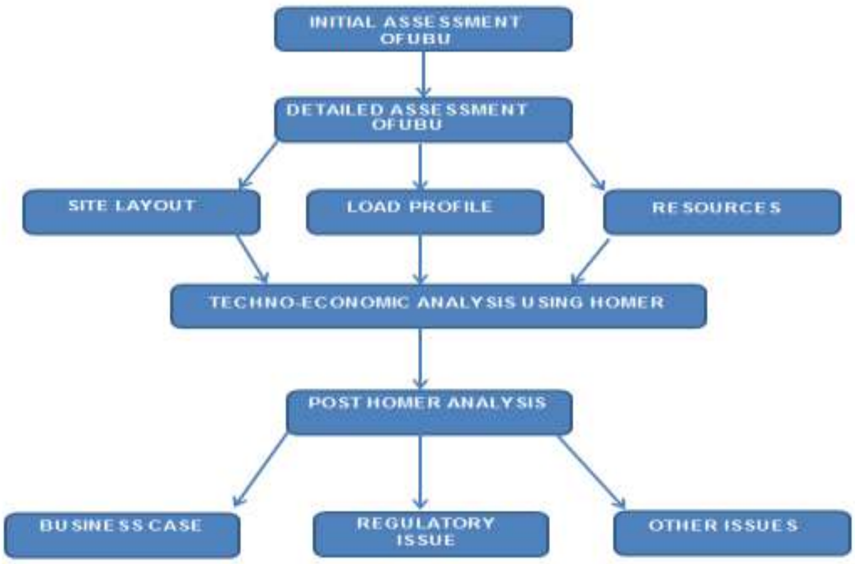


Figure 7: Flow Diagram of the Study

In the study, Solar PV (SPV) system, a converter, and a battery bank were used in combination with standby diesel set to compensate for shortfalls of power during bad weather conditions that are not favorable for the system .See Fig 8 Schematic below:

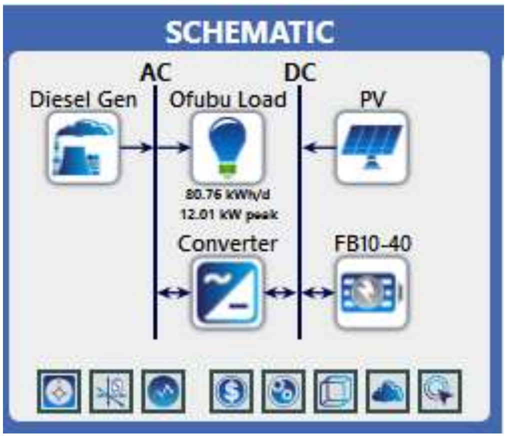


Figure 8: Design of the Selected Renewable Energy Technology for the System

4.1 SYSYTEM MODELLING

The details of the village used for the study are listed in table 1. The nearest town is Patani, in Delta State, which is about 3 to 4 kilometres away from Ofubu, New Patani. Ofubu is located in close proximity to Patani and East-West Road. The area around the village is partially bushy with flat plains. The village has no access to electricity grid which offers an opportunity for off-grid electrification and its source of water is from the river. NDDC made available portable water through solar powered hand pumps that are now defective as at the time of carrying out this research.

Table 1: Details of Ofubu Village

PARTICULARS	DETAILS
Village Name	Ofubu (New Patani)
Nearby Town	Patani
Local Government Area	Sagbama
State	Bayelsa
Country	Nigeria
Latitude	5°13.7'N
Longitude	6°12.2'E
Area of Village (in hectares)	300
Forest land (in hectares)	>180
River available	1
Water facility	2
Grid Electricity	0
Number of households	30
Total population	109
No. Males	48
No. Females	61
Educational facilities (Primary school)	1
Medical Facilities	0

4.2 VILLAGE LOAD ASSESSMENT

In a remote rural village, the demand for electricity is not high compared to urban areas. Electricity is demanded for domestic use (for appliances like radio, compact fluorescent lamps, ceiling fans, refrigerator and table fans), agricultural activities (such as water pumping), community activities (such as in community primary school) and for rural commercial and small-scale industrial activities (such as fish storage, small palm oil processing plants and cassava processing activities). In this study, the energy load requirement is carefully estimated considering existing load profile data available by physical assessment. The demand has been estimated considering household load use patterns commercial activities, and energy use in productive applications. Table 2 provides summary of estimated demand.

Table 2: Estimated Electricity Demand for Ofubu Village

S/N	Load	No. In Use	Power (Watts)/Unit	No. In Use x Power (Watt)	Hrs/Day	Watt-Hrs/Day
1	Low-energy Lights	60	8	480	20	9600
2	Security Light	50	18	900	12	10800
3	Street light	4	100	400	12	4800
4	Ceiling Fan	20	30	600	10	6000
5	Standing Fan	5	15	75	10	750
6	Refrigerator	2	600	1200	15	18000
7	Television	4	100	400	18	7200
8	Radio	20	10	200	12	2400
9	Water pump	1	745.6	745.6	4	2982.4
10	Local Palm Oil processing machine	2	745.6	1491.2	8	11929.6
11	Cassava Grinding Machine	1	745.6	745.6	8	5964.8
12	Others(Phone & Small devices)			200	20	4000
TOTAL						**84426.8**
Average						**80760.13**

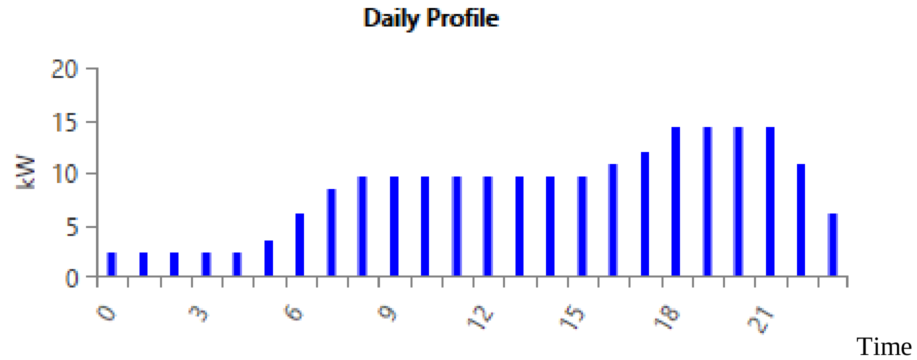


Figure 9: Daily Load Profile of Ofubu village

4.3 RESOURCES ASSESSMENT

The solar resource used for Ofubu village at a location of 5°14'N latitude and 6°13'E longitude was taken from NASA Surface Meteorology and Solar Energy website. Annual average solar radiation was scaled to be 4.53kWh/m2/Day and average clearness index was found to be 0.456. The solar radiation is available throughout the year; therefore a considerable amount of PV power output can be obtained (see Fig. 10).

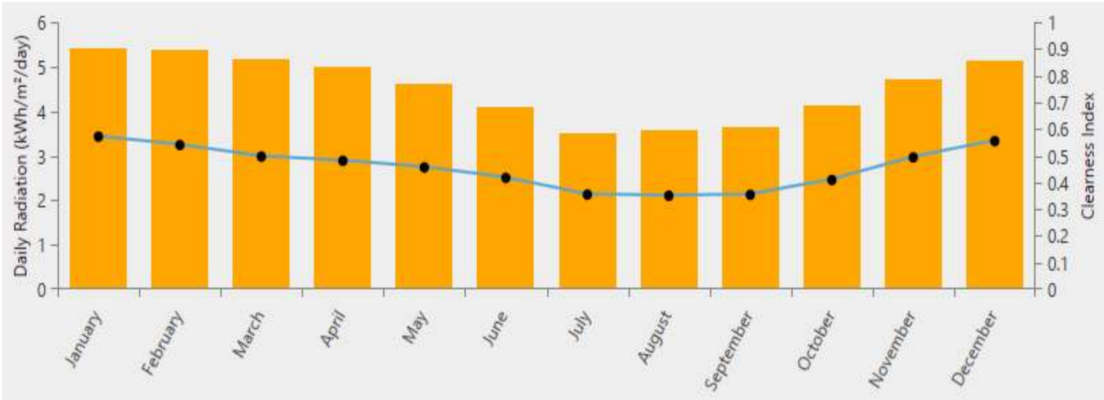


Figure 10: Solar energy profile at Ofubu village

Diesel fuel is predominantly refined from crude oil. Diesel can be used to run diesel engines and with minor engine modifications (if required). Bio-diesel fuel and ethanol can also be used to reduce carbon emission in the future, since the raw material for bio-fuel and ethanol are in abundant in Ofubu and its environs. In the Niger Delta region, there are two refineries one in Warri and the other in Port Harcourt, both are functional but not working in full capacity, it is assumed that the fuel will be available from these refineries or nearby fuel stations in Patani town. There will be minimal environmental impact because, in the study, the generator is required to run only when there is shortfall of power and very little carbon emission to air. The fuel price is considered to be ₦250/L. The current market price of diesel in Nigeria is between ₦180/L to ₦280/L, though it varies regionally due to tax and other costs.

4.4 COMPONENTS ASSESSMENT

In a micro-power system, a component generates, delivers, converts and stores energy. In this analysis, solar PV is the intermittent resource and the diesel is kept for backup. Batteries and Converter are for storing and converting electricity respectively. Though the Stand alone SPV is viable and can operate independently. The backup generator connection in this study is only used to enable robust design to prolong battery life and improve efficiency. Performance and cost of each of the system's components is a major factor for the cost results and the design. SPV panels are connected in series. Power generated by SPV is sufficient for this location due to its average solar irradiance of 4.53kW/m^2/day. Capital and replacement cost for a 1kW, SPV are taken as ₦380,000 and ₦375,000 respectively. As there is very little maintenance required for PV, only ₦500/year is taken for O&M costs. Like for all other components considered, the costs per kW include installation, logistics and dealer mark-ups. SPV is connected to a DC output with a lifetime of 25 years. De-rating factor considered is 80% for each panel to approximate the varying effects of temperature and dust on the panels. Panels are modeled as fixed titled south at 19°59' N latitude of the location with slope of 45° considering diesel generator of 10kW. The amount of electricity generated greatly depends on availability of power from SPV used as backup. Cost of 1kW is taken as ₦28,000, while replacement and maintenance cost are considered to be ₦25,000 and N5/hr. respectively. Diesel generator has lifetime of 87,600 hrs (10 years). The Generator has maintenance cost of ₦10,000 for oil change out and servicing every 4000hrs. Batteries are used as backup and to maintain constant voltage during peak loads or a shortfall in generation capacity. The battery chosen for this study is CELLCUBE® FB 10-40. It is a 48V battery pack with nominal capacity of 833.33Ah (40 kWh) with lifetime throughput of 876,000kWh. Capital, replacement and O&M costs for one unit of this battery were considered as ₦500,000, ₦450,000 and ₦500/year respectively. These batteries are modeled based on charging and discharging cycles. Capital, replacement and O&M costs of the converter for 1kW systems were considered as ₦20,000, ₦15000, and ₦10/year respectively. Lifetime of the converter is 15 years, inverter efficiency of 90% and rectifier efficiency of 85% are used.

4.5 SENSITIVITY OF INPUTS

The key variables for micro-power system are, however, often uncertain. This is a major problem to be overcome in the designing of the system. Here the uncertainties in the discount rate and diesel price have been taken into account. The sensitivities entered for the diesel price are ₦150/L, ₦200/L, and ₦250/L.

4.6 ECONOMIC MODELING

Since the aim is to minimize total Net Present Cost (NPC) both in finding the optimal system configuration and in operating the system, economics play a crucial role in the simulation. The indicator chosen to compare the different configurations' economics is the life-cycle cost (LCC), and the total NPC is taken as the economic figure of merit. All economic calculations are in constant Naira terms. Project's lifetime is considered to be 25 years with annual discount rate of 10%. The system fixed capital cost is considered to be ₦2,500,000 for the whole project and fixed O&M cost is estimated to be ₦180,000/year for the project lifetime. System fixed capital costs include various civil constructions, logistics, labor wages, required licenses, administration and government approvals and other miscellaneous costs.

4.0 ANALYSIS

A number of prospective design configurations were investigated. After examining every design, the one that meets the load and system constraints at the least life cycle cost is selected. Optimization and sensitivity analysis across all mentioned components and their resources, (technical and cost parameters, system constraints and sensitivity data over a range of exogenous variables) are investigated. The competitiveness of the best suited hybrid Renewable Energy Technology (RET) system for rural electrification is compared with the conventional option of grid extension, based on the COE for both options and based on this the economic distance limit (EDL) is determined. Cost of low tension distribution lines within villages has been excluded since it is the same in all the cases. Optimal combination of RET system components for the case study is 30kW, PV-Array, 8kW diesel generator, 3 Strings CELLCUBE® FB 10-40 Batteries, 10kW Inverter and Rectifier with dispatch strategy of cycle charging. (Fig.11). Total net present cost, capital cost and cost of electricity (COE) for such hybrid system are ₦21.1M, ₦11.4M, and ₦66.06/kWh respectively. COE of ₦66.06/kWh from this hybrid system is costlier than that of ₦24.91/kWh- for Port Harcourt Electricity Distribution Company (PHEDC) for grid extension as considered for this study. Therefore grid extension does appear to be a viable option to meet the village load. But, since there is no grid supply; electricity from Hybrid system becomes viable.

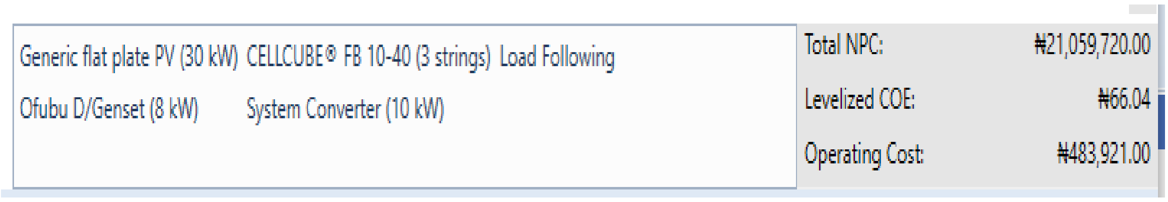


Figure 11: System architecture and cost summary

Table 3: Optimal least cost hybrid system for the case study

Production	kWh/yr	%
Generic flat plate PV	39,926	91.40
Ofubu D/Genset	3,755	8.60
Total	43,681	100.00

Figure 12 shows the monthly distribution of electricity produced in kW by SPV and DG (Diesel Generator). From January to December, SPV is mostly used combined with very little power from the DG to maintain battery charge. From the graph, it is clear that the DG produce less than 2kW of electricity throughout the year. This confirmed the fact that the SPV can actually run alone, with little load management and the DG is mainly for robust design. The penetration of solar energy reduces diesel output, particularly during February, April, May and June. Solar panels produced 39,926 kWh/year which is 91.40% of total power required. The levelised cost of solar electricity turns out to be ₦66.04/kWh.

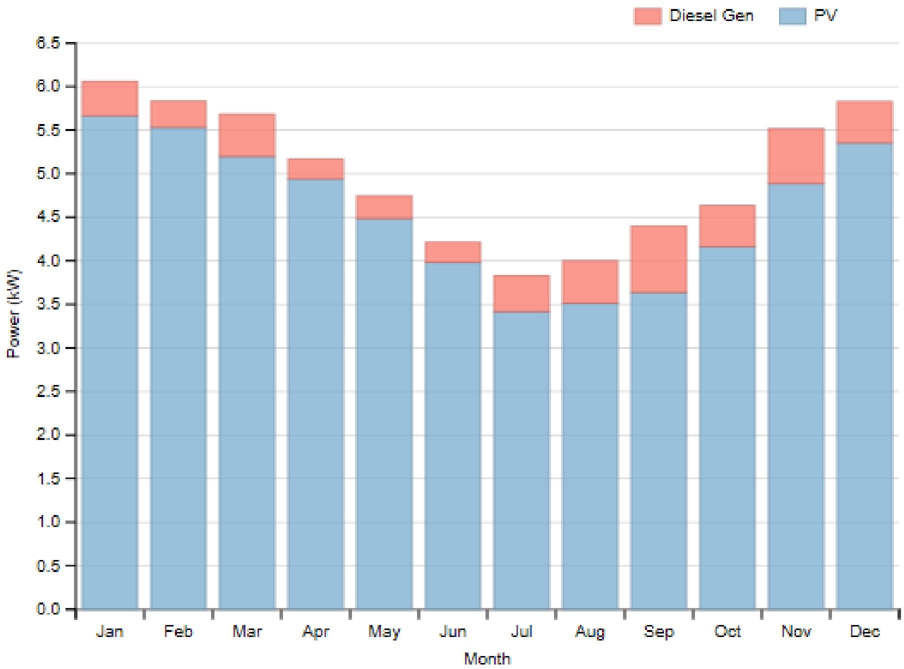


Figure 12: Monthly Distribution of the Electricity Produced in kW

Table 4: Optimized Total System Cost

Component	Capital (₦)	Replacement (₦)	O&M (₦)	Fuel (₦)	Salvage (₦)	Total (₦)
CELLCUBE® FB 10-40	₦1,500,000.00	₦298,183.00	₦16,228.00	₦0.00	(₦153,314.00)	₦1,661,097.00
Converter	₦200,000.00	₦48,329.00	₦1,084.00	₦0.00	(₦7,571.00)	₦241,842.00
Generic flat plate PV	₦11,400,000.00	₦0.00	₦16,228.00	₦0.00	₦0.00	₦11,416,228.00
Ofubu D/Genset	₦224,000.00	₦0.00	₦835,360.00	₦2,252,543.00	(₦18,808.00)	₦3,293,095.00
Other	₦2,500,000.00	₦0.00	₦1,947,487.00	₦0.00	₦0.00	₦4,447,487.00
System	₦15,824,000.00	₦346,512.00	₦2,816,387.00	₦2,252,543.00	(₦179,693.00)	₦21,059,749.00

Table 5: SPV Optimized Result

Quantity	Value	Units
Rated Capacity	30.00	kW
Mean Output	4.56	kW
Mean Output	109.39	kWh/d
Capacity Factor	15.19	%
Total Production	39,926.00	kWh/yr

Quantity	Value	Units
Minimum Output	0.00	kW
Maximum Output	29.2	kW
PV Penetration	135	%
Hours of Operation	4,418	hrs/yr
Levelized Cost	26.4	₦/kWh

Table 6: DG Optimized Results

Quantity	Value	Units
Hours of Operation	1,374	hrs/yr
Number of Starts	316	starts/yr
Operational Life	63.8	yr
Capacity Factor	5.36	%
Fixed Generation Cost	84.4	₦/hr
Marginal Generation Cost	41.0	₦/kWh

Quantity	Value	Units
Fuel Consumption	1,388.00	L
Specific Fuel Consumption	0.37	L/kWh
Fuel Energy Input	13,658.00	kWh/yr
Mean Electrical Efficiency	27.50	%

Quantity	Value	Units
Electrical Production	3,755.40	kWh/yr
Mean Electrical Output	2.73	kW
Minimum Electrical Output	2.00	kW
Maximum Electrical Output	8.00	kW

It is evident from Fig. 12 and table 5 that SPV station dominates the electricity output in this case. The SPV operates at full load for 12 months and produces 39,926kWh/year, achieving a capacity factor of 91.40% and operate for 4,418hrs/yr. At this level of operation, the levelised cost is ₦26.4/ kWh. The SPV plant becomes the dominant producer. For the selected system the diesel plant operates for 1,374hrs/yr (capacity factor 5.36%), produces 3,755.40 kWh/year and consumes 1,388 litres of diesel fuel as shown in table 6.

Table 7: Best Hybrids and SPV only - Parameters

Configuration	**Unit**	**Best Hybrid**	**SPV only**
Diesel price	₦/L	150	0
Solar PV	kW	30	40
Batteries- CELLCUBE® FB 10-4	(Strings)	3	10
Converter	kW	10	10
Total Capital Cost	₦	11,400,000	22,900,000
Total NPC	₦	21,059,724	25,447,960
Total Annual Capital Cost	₦/yr	1,462,561	2,116,573
Total Annual Replacement Cost	₦/yr	32,027	96,334
Total O&M Cost	₦/yr	260,310	187,100
Total Fuel Cost	₦/yr	208,195	0
Total Annual Cost	₦/yr	1,946,484	2,352,073
Operating Cost	₦/yr	483,921	235,500
COE	₦/kWh	66.044	79.823
PV Production	kWh/yr	39,926 (91%)	53,234 (100%)

Diesel Generator	kWh/yr	3,755 (9%)	0
Total Electrical Production	kWh/yr	43,681	53,234
AC Primary Load	kWh/yr	29,472	29,466
Unmet Load	kWh/yr	5	11
Excess Electricity	kWh/yr	3,515	11,258
Capacity Shortage	kWh/yr	14	29

For the Best Hybrid System, 3,515 kWh/year of electricity which is 8% of total electricity generated goes unused due to low demand and is fed to dump loads as indicated in table 7. This shows that this system has the capability to meet future growth demand. It is worthy of note that as demand increases, load factor increases and hence cost per kWh decreases.

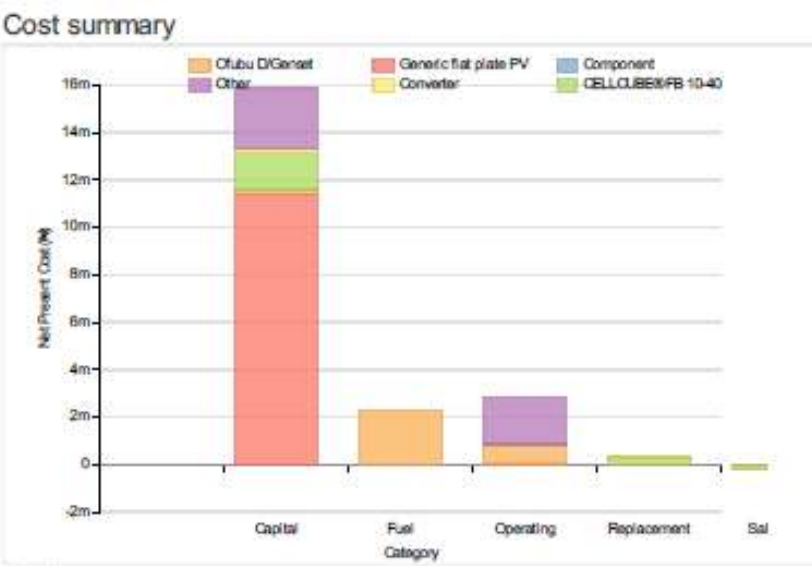


Figure 13: Cash flow summary based on the selected components

Figure 13 shows cash flow summary for the optimal system. The capital cost of diesel generator makes up only 1% of the system's total capital cost, whereas almost 71% of the initial investments goes to SPV arrays System. Once installed, however, SPV is cheap to maintain and operate compared to the DG, which in the end is responsible for 28% of the system's total annual cost of ₦1, 946,484.

4.2 SENSITIVITY RESULTS

Sensitivity analysis eliminates all infeasible combinations and ranks the feasible combinations taking into account uncertainty of parameters such as future developments (i.e. increasing or decreasing load demand), changes regarding fluctuations in diesel prices etc. Various sensitive variables are considered to select the best-suited combination for the hybrid system to serve the load demand. If the diesel option is not available, the second-best hybrid configuration will comprise of 40kW SPV, 10kW system converter and 10 strings of CELLCUBE ® FB 10-40 batteries and will have electricity cost of ₦79.82/kWh and generates 11,258kWh/year of excess electricity. This configuration can be used at off-grid locations when diesel generator and conventional grid are not available. This shows that the system configurations with SPV only tend to be more costly than other Diesel-PV hybrid technologies because the number of PV and batteries will have to increase but in the long run it is preferable. Diesel price is fixed at ₦150/L, ₦200/L and ₦250/L with NPC value of ₦21.1M, ₦21.8M and ₦22.6M respectively. This shows that with change in sensitivity variables, the capacity of an individual component increases and hence the configuration of the system changes. Therefore hybrid system with Diesel-SPV proves to be the cheapest option compared to standalone SPV.

4.3 EMISSIONS

The optimal hybrid RET system would save 19,647 kg/yr of CO_2 over one year in operation compared to a central power generation plant or a stand-alone DG system. In addition, emission of particulate matters and nitrogen oxides will be reduced due to reliance on renewable energy systems (see table 6).

Table 6: Emissions

Emissions

Pollutant	Emissions	Units
Carbon dioxide	3655	kg/yr
Carbon monoxide	9	kg/yr
Unburned hydrocarbons	1	kg/yr
Particulate matter	1	kg/yr
Sulfur dioxide	7	kg/yr
Nitrogen oxides	81	kg/yr

V. Conclusion And Recommendation

Search for a technically feasible and economically viable hybrid solution for off-grid electricity supply to a remote village such as Ofubu, New Patani resulted in a least-cost combination of a small diesel generator, SPV and batteries that can meet the demand in a dependable manner at a cost of ₦66.04/kWh. Given the availability of small diesel generator in this location, most of the electricity in the optimal solution comes from SPV plant and it provides cheap source of power to the locality. However, the system reliability cannot be ensured due to variable nature of imported battery quality and lack of constant diesel supply due to the country's inability to optimize her refined crude oil product like diesel. There is an intermittent scarcity of refined petroleum products in Nigeria, thus making the pump price of diesel skyrocket and difficult to predict. Diesel and solar PV plants sources contribute to electricity generation but costlier options than DISCO grid supply in the short run. If the DISCO grid is not available, electricity demand can be met with hybrid system comprising of solar PV plant and small diesel plant. But the cost of electricity supply will increase three folds, thereby making the system less attractive to users. The study considered local demand in details and have included multiple types of users (residential and agricultural) and considered variations in the demand. Finding the least cost combination of supply options to meet the demand. Realistic demand estimation assumes an important role. The study contributes in this area by highlighting this aspect and incorporating detailed demand analysis feature in the study. The study briefly considered the financing challenge, business model selection, tariff issue, possibilities of running SPV micro-grid and regulatory concerns. This is an attempt to go beyond the techno-economic analysis. Even demand scenarios can be included to take the simulations to another level of iteration. Similarly, a systematic approach of considering the business case for the optimal solution and its delivery-related issues can enhance the overall appreciation of the micro-energy systems. The study can be done on the possibility of producing PV Cell/Panel and batteries here in Nigeria to reduce the huge cost of importation.

The following are recommendations based on the study carried out.

- Where solar potential exists, like in the six geopolitical regions- it is important to take advantage of the resource;
- A combination of technologies improves supply reliability and hence makes better business sense;
- The cost of supply of renewable-energy-based electricity may not always be a cost effective option for remote applications unless appropriately supported by the government.
- Standard template can be designed for a systematic estimation of demand for off-grid areas and to capture the stakeholder perspectives.

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