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Hybrid Renewable Energy System for Rural community of Sub-Saharan Africa.

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Acknowledgements

This thesis is dedicated to my God, Jehovah, my creator and the Lord Jesus Christ my Saviour, for you have honored your word above your names in my life. Psalms 138:2[B].

“For I know the plans I have for you," declares the LORD, "plans to prosper you and not to harm you, plans to give you hope and a future. ” Jeremiah 29: 11, NIV.

“For when I called upon you, you answered me, you have showed me great and unsearchable things I never knew.” Jeremiah 33: 3, NIV.

I will also like to thank my wife, Dr. Dulcidia Oniyere, and my lovely daughters, Daphne and Shivon, for their endless love and support during the course of this Master’s programme.

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Abstract

The thesis analyses the current energy situation in most rural communities in Nigeria, and the impact of renewable energy system on the economy in such areas, with a particular emphasis on Agharha – Otor.

In areas with no grid connection, such as the case study location, diesel generators are usually the only available option for energy generation. Due to the high operational cost it is necessary to consider other means of energy production. Since such communities have an average of around 10 – 12 hours of sunshine a day, solar energy becomes a most economical means of renewable energy generation.

The hybrid renewable energy system (HRES) proposed in this thesis is the combination of a diesel generator and a PV system working together, with the aim of matching the energy demand of the community. This thesis evaluates the major issues to address in diesel/PV hybrid energy system design such as cost and technical performance in realtion to energy demand matching.
Feasibility studies assuming present day costs, lower future costs and lower future costs with government subsidy were carried out on 4 HRES configurations: (a) diesel generation only, (b) PV generation only, (c) a PV system with energy storage and (d) a PV/diesel hybrid system.

In each case an environmental and reliability assessment was carried out so that an informed decision can be made in choosing the best technology to meet the energy needs of the community.

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List of Abbreviations

AC	Alternating current
DC	Direct Current
HRES	Hybrid renewable energy system
PV	Photovoltaic

List of Symbols

$	Dollar
kW	kilowatt
kWh	Kilowatt-hour
yr	Year
h	Hour
T	Temperature

1. Project definition

Many villages and some towns in Nigeria live in energy poverty, with little or no supply from the main grid, and are forced to be heavily dependent on diesel generators that can barely meet demand due to insufficient generator capacity or fuel availability, not considering the financial impact, noise and air pollution that accompanies diesel generators.

The reliability issues associated with photovoltaic components can be mitigated when combined with an energy storage system or a diesel generator. This project undertakes a feasibility study of a hybrid system in which PV and diesel generation complement each other to meet community energy demand, reduce cost and improve standard of living.

The international policy focus on climate change is encouraging the uptake of renewable energy technologies . Since 1970 much investment have has been made to increase the deployment of renewable technology, but issues such as high capital cost and lack of effective energy storage still poses a threat to the future utilisation of renewable technologies such as photovoltaic components. Photovoltaic systems are a clean and reliable (if properly managed) source of energy. It is sustainable as it is generated from solar energy, but due to the limitation of solar availability it cannot operate as a standalone means of energy supply. Thus a hybrid energy system is appropriate, achieved by the addition of a diesel generator to work either as a backup to or in parallel with the PV system.

A hybrid generation energy system is the combination of two or more energy sources to operated either jointly or to complement each other in order to meet demand. Such a system may also include an energy storage unit. Since PV power output is direct current (DC), it is necessary to use an inverter device to convert the DC to AC current before distribution (IED, 2013). The proposed hybrid energy system in this study consists of a photovoltaic component and diesel generator for electrification of the rural area of Agbarha –Otor of Nigeria. The proposed scenario will use the diesel generator either as a standby option or working together side by side. This system will not only be beneficial but also a competitive means of energy generation compared to other conventional sources, as there is little maintenance and operational cost associated with the PV systems (M.S. Ismail, 2016).

The monthly solar data for the case study location (Agbraha – Otor) was collected, as shown in Tables 1 and 2, with an average of 5.2 kWh/m^2 per day. Three economic scenarios were analyzed, each containing four energy system configuration options.
A financial feasibility study was carried out to determine the most cost-effective option for the community. The Nigeria government has set aside 100 million dollars for renewable energy grants with the intention of reducing carbon dioxide emissions by 30% by the year 2030. Assuming the community is granted a loan from the federal government for this project, a loan repayment analysis has been carried out with a 25 year repayment period.

Reliable energy supplies are a major challenge in most African countries, especially in the rural communities and Agharha – Otor, Ughelli - North, and Delta State in Nigeria is not an exception. Nigeria's vast wealth in crude oil has made her fully reliant on fossil fuels for power supply. The country is set to expand reliance on renewable energy to 50% by the year 2020. Due to the lack of affordable energy supplies in rural areas the standard of living is poor, making even clean drinking water a scarcity.

In sub-Saharan Africa 89% of the population depend on the use of biomass in the form of wood, charcoal or other agricultural products. Since most rural communities in Nigeria are located in areas with high solar insolation, and given the constant depreciation in the prices of solar panels, photovoltaic technology is becoming a popular means of energy generation amongst these communities (Ifegwu Eziyi, 2014).Communities also benefit from renewable energy deployment through job creation, economic growth, better standard of living and, of course, a cleaner local ait quality. In rural areas generation of electrical power supplies is usually through fossil fuels, which is expensive, hence the increased need to invest in renewble means of energy generation.

1.1 Scope of thesis

The project analyzes different energy system configuration options, including a diesel only generation, PV only generation, PV with storage, and PV and diesel generation. These systems are assessed in order to establish the most cost effective solution. The objective overall is to determine how best to fraise the standard of living in the rural communities of Nigeria by means of reliable energy supply. The hybrid system proposed in this project is used to eliminate or mitigate the weakness of a standalone energy system.

Three economic scenarios are applied to the 4 energy system configurations. The first is a present day cost analysis, the second is lower cost future option, and the third is as option 2 but with government subsidy. Each of the economic scenarios are applied to 4 energy generation options as follows.

Option A, which is a diesel generator only system designed to meet a demand profile of 5 MW with a 24 hour operation period. Option B, which is a PV system,. Option C, which is a PV system with energy storage added. Option C, which is a PV/diesel hybrid system.

1.2 Methodology

The approach involves the creation of a mathematical model of the above energy systems, which can then be subjected to the 3 economic scenarios. A feasibility study of different energy technologies is conducted, and the cost effectiveness of each scenario compared. This takes into account the capital, operational and maintenance costs as well as the environmental impact and reliability of all technologies (Ahmad Agus Setiawana, 2014). Different economic scenarios, such as present cost possible lower costs in future were assumed and applied to systems comprising a standalone diesel generator, an automonous PV sysytem, a PV system with battery storage, and a hybrid system with cooperating diesel generator and photovoltaic system.

1.3 Thesis outline

Chaper 2 reports a literature review that describes the energy demand of the case study site. Chapter 3 describes the case study site in terms of its location, available resources, load profile and existing energy technology. Chapter 4 reports the economic scenarios considered and the results obtained. Finally, chapter 5 reports the conclusion and possible future work.

2. Literature review

This chapter reports the demand profile of the targeted area, the collection of information for the various technologies considered, and the modeling method used in this project.

2.1 Demand Profile

A typical energy efficient home with an family size of 4 consumes around 50 kWh/day (Green Energy Efficient homes, 2016). This usage has been modified for the purpose of the analysis of the case study area, which comprises 1,000 homes, a factory, a clinic, a primary school, a secondary school and a pipe bore water generation system.

Figure 1 shows how the energy is distributed; it can be seen that the factory and homes are the largest energy consumers. The average peak demand is 3.2 MW.

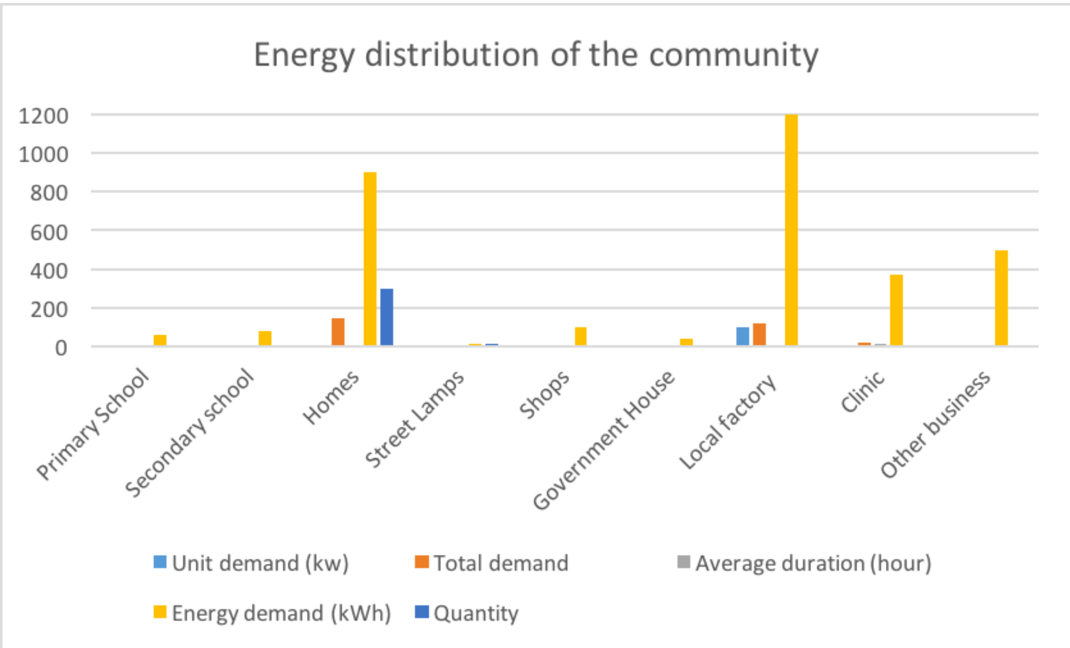

Figure 1: Energy distribution of the community.

The hourly energy demand profile for the community can be seen in figure 2, which shows the maximum demand to be between the hours of 10 am 3 pm, a period well matched to the energy that can be harnessed from a PV system since the community gets an average of 10 hours of sunshine per day.

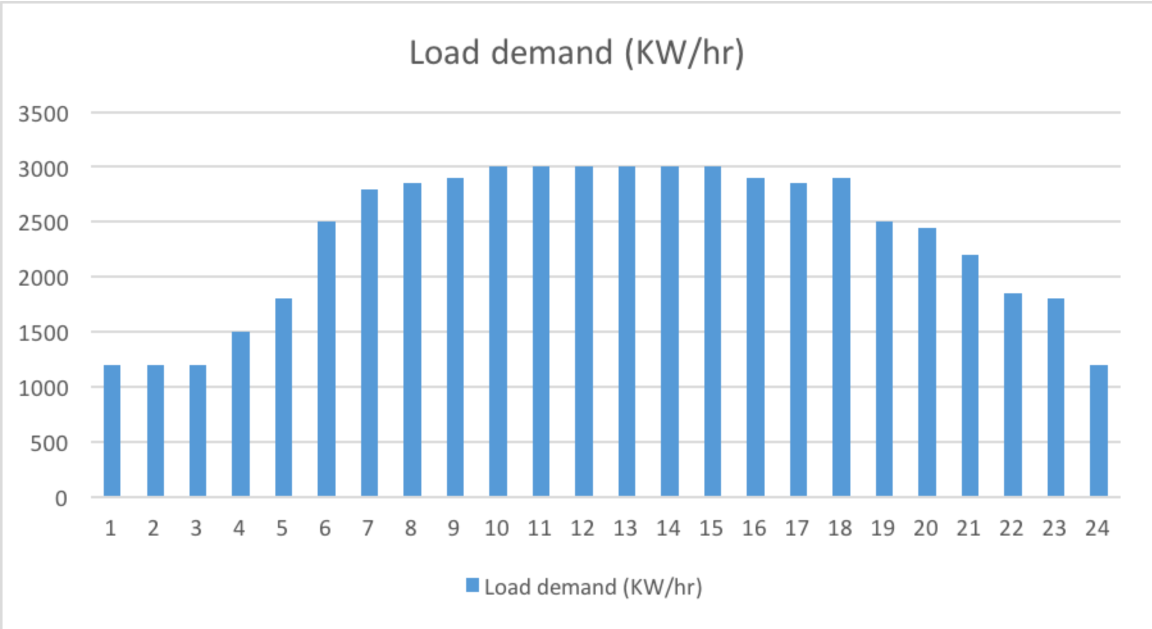

Figure 2: Community demand profile.

The yearly energy demand for the case study is shown in figure 3, with the maximum demand required in March, April, May, June and December according to literature review.

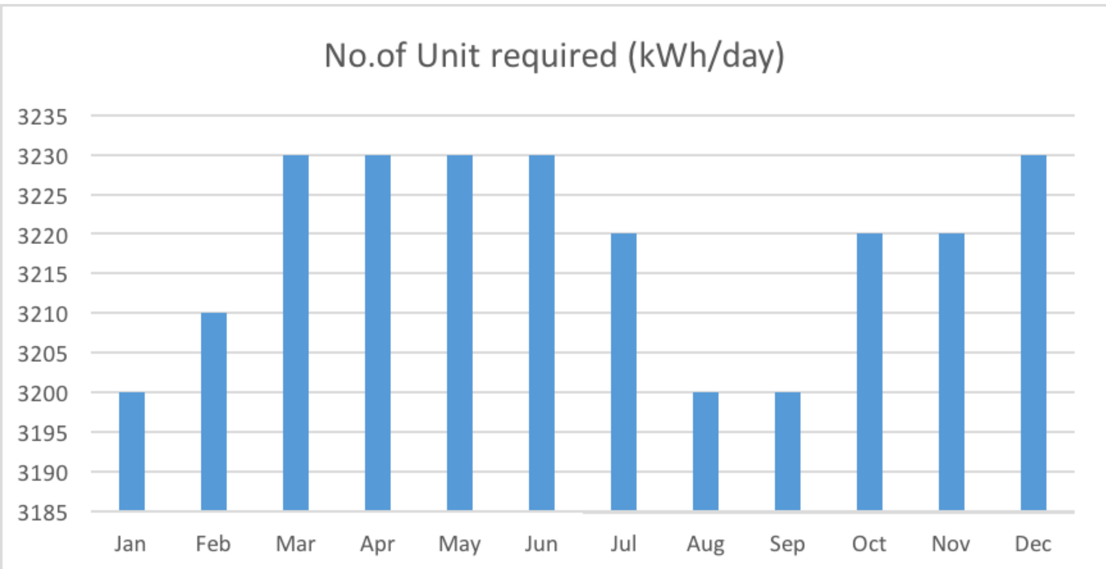

Figure 3: Units required per data.

2.2 Diesel systems

In Nigeria, due to the insufficient supply of power from the main grid, 90% of businesses and at least 60% of homes presently use diesel-powered generators, meaning that there are about 15 million diesel generators being used in Africa's most populated nation. Diesel emissions coming from domestic use, commercial use, buses and trucks poses a great risk to the environment and human health, mostly due to the duration of usage. Exhaust from diesel engines contains more than 40 toxic air contaminants, also many of these pollutants have known and unknown health effects. In addition, pollution substances such as arsenic, formaldehyde and benzene are suspected of causing cancer, as well as cardiovascular and respiratory diseases. Diesel emissions also contain other substances such as nitrogen oxide that causes air, water and soil pollution. They also cause poor visibility and noise pollution (Awofeso, 2011).

Although diesel technology is reliable and can be setup anywhere, it should not be used as a sole source of energy supply due to the operational cost and the environmental impact. This technology is optimal when used as a backup system or only at peak demand. The engine is the energy source of the system, while the power output supply of the system is directly proportional to the size of the engine. On the other hand, regular maintenance is required to prolong the lifespan and efficiency of the engine.

A diesel generator comprises a compression-ignition engine and a generator or alternator. The major purpose of a diesel generator is conversion of fuel (diesel) into electricity. The diesel system does not literally generate electricity, however the mechanical energy it creates forces the wiring of the electric circuit and this causes the flow of electrical charges. Diesel generators are mostly used in areas with no connection to the main grid, as backup power, in the or as a means to match demand in peak periods (Wikipedia, 2016).

Efficiency is the ratio of the energy output to the energy input, i.e. the ratio of the electrical energy generated to the amount of diesel consumed. The efficiency of the system could range from 50% to 90% depending on the age of the system. The losses incurred are related to heat dissipation, the inefficiencies associated with friction and the generator.

The alternator is an electromechanical device that generates the electrical output from the mechanical input created by the engine, and is also known as an AC synchronous generator. The alternator consists of moving and stationary parts, working together causing the motion between the electric and the magnetic fields, therefore creating electricity.

Another important part of the diesel generator is the radiator, which is designed for the cooling of the internal combustion of engines. This is done by the circulation of a coolant to the engine block. The cooling system absorbs 20 - 30% of the heat input generated by the fuel to the engine.

The control panel is one of the most complex parts of the system machinery that enables the operator to monitor the efficiency and system condition.

The battery charger used for this system is rechargeable, it supplies electric power that powers the control panel and starter motor of the generator. This keeps the generator battery charged by supplying it with float voltage, when the float voltage is low the battery is undercharged. The battery is designed to function automatically without requiring any manual setting and it is made of stainless steel to prevent corrosion (Diesel Services Supplies, 2016).

The running cost for the system, as determined from the current diesel price in Nigeria according to global petrol prices (Global petrol prices, 2016), is $1.8 per gallon as at August 2016. Consequently, it will cost an average of $11,193/day to operate the system if utilised for 24 hours, costing approximately $4 million per annum.

Table 1 shows the average fuel consumption for the proposed diesel generator set of 5 MW. From this table it can be seen that a 5 MW diesel system will require 6218.4 gallons of fuel to operate at ¾ load capacity. The mathematical model of the fuel consumption is given in appendix C.

Table 1: Approximate diesel generator fuel consumption (Diesel services and supply, n.d.)

Generators Size (kW)	¾ load (gal/hour)
2000	103.5
2000	103.5
1000	52.1
5000	259.1
5000 if operated for 24 hourse	6218.4 gallons

This system will require an average of 2-24 maintenance visits a year. For a system that is required to run for 24 hours, 365 days a year the numbers of annula maintenance visits will rise to at least 12 - 15 for the first 5 years, costing a total of $100,000 - $350,000/annum (Kurtz, 2014). A mathematical model for the fuel consumption is given in appendix D.

2.2.1 Modeling of diesel generator

The overall efficiency of a diesel generator system can be calculated using the following formula:

$$\eta_{Overall} = \eta_{brake\ thermal} \times \eta_{generator}$$

where:

$\eta_{brake\ thermal}$ = Brake thermal efficiency of the diesel engine

$\eta_{generator}$ = efficiency of the generator.

There are many different approaches to modeling a diesel generator, but part-load efficiency method was adopted because of its simplicity.

2.2.2 Types of diesel system

Diesel systems come in small, medium and large sizes, and feature either a two or four stroke cycle engine. They are usually classed by the amount of their power output.

2.2.3 Cost of diesel systems

The cost of a diesel systems varies with the size of the system. For the purpose of this analysis, two 2.5 MW systems are choden costing a total of $3.5 million.

2.3 PV systems

Solar energy is the process of harnessing the energy from the sun, it is arguably the cleanest and most reliable source of sustainable energy technology available today, and can be used to power homes and businesses.
Solar energy generation can be classified either as solar electric or solar thermal energy convertion, and the device used for converting solar into electrical energy is known as the photovoltaic (PV) cell (Shaahid, 2006). Solar PV systems are designed to convert the shortwave radiation from the sun into electrical energy by exciting the electrons in the silicon cells in semiconductor material using the photons from the sunlight (NW wind and solar, 2015).

Solar PV systems can be installed anywhere and are relatively easy to install compared to other sources of renewables (Green, 2012). However, their major limitation is that they cannot be operational for 24 hours; most parts of the world receive only 6 – 12 hours of sunshine a day, depending on the season, hence making solar PV systems an unreliable means of energy generation. Moreover, PV systems require additional components such as an inverter, which converts DC electricity to AC before being fed to the electrical grid. Without this component the DC output can be stored locally in a batteryPV systems have an efficiency of 14 - 25%, which is low compared to other sources of renewable systems. They are also prone to destruction from wildlife as they are quite fragile and require much land for large installations (Green, 2012).

2.3.1 Modeling of photovoltaic system

There are various ways of modeling a PV system, and the method used here is suitable implementation in an excel spreadsheet. The mathematical modeling of a PV panel output is given in appendix C. The input energy to the PV system is solar radiation with the total irradiance of an inclined surface given by:

$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r$

where:

I_b = Direct Normal

I_d = Diffuse solar radiation

R_d = Tilt factors for diffusion

R_r = Reflected part of the solar radiation.

The total amount of radiation received by the panels depends on the posi

tion of the sun and the inclination/orientation of the panel (Deshmukha, 2006):

$\eta = \eta_m \eta_{pc} P_f$

where:

η = efficiency of the system

while the module efficiency, η_m, is

$\eta_m = \eta_r [1 - \beta(T_c - T_r)]$

where:

η_r = reference efficiency (under standard test conditions)

η_{pc} = power conditional efficiency

P_f = packing factor

β = temperature coefficient

T_c = reference temperature

T_c = operational temperature

2.3.2 Types of PV panels system

The following are the commercial PV panel available today.

- Monocystalline silicon
- Polycrystalline silicon
- Thick-film silicon
- Amorphous silicon
- Cadmium telluride
- Copper indium dieseline.

Gallium arsenide cells are only used in rare occasion such as powering solar cars and satellites. The monocrystalline silicon panel has the highest efficiency achieving 15% – 20%; it also has the longest lifespan, hence is the PV panel type of chosen for use in this project (National energy foundation, 2016).

Table 2.0 shows the efficiency of the most efficient PV panels available in the market today. The SunPower X21-345 model has been selected for the present study.

Table 2: Efficiency of PV panels (The Eco expert, 2007)

Manufacturer	Model	PV type	Module Efficiency
SunPower	X21-345	Monocrystalline	21.5%
Ja Solar	JAC M6PA-4	Monocrystalline	20.9%
Sanyo	HIT Double 195	Monocrystalline	20.5%
SunPower	327-320	Monocrystalline	20.4%
AUO	SunForte PM318B00	Monocrystalline	19.5%
Phono Solar	PS330P-24/T	Polycrystalline	17.0%

2.3.3 Cost of PV panels

The PV industry is growing rapidly due to the abundant and free availability of solar resources and figure 4.0 shows the cost reduction over time. The figure illustrates a constant declining trend of PV prices over the years for a monocrystalline silicon panel, assuming the gradual decline in the prices of the PV panels continues till 2020 the prices of PV system will be below $1/W.

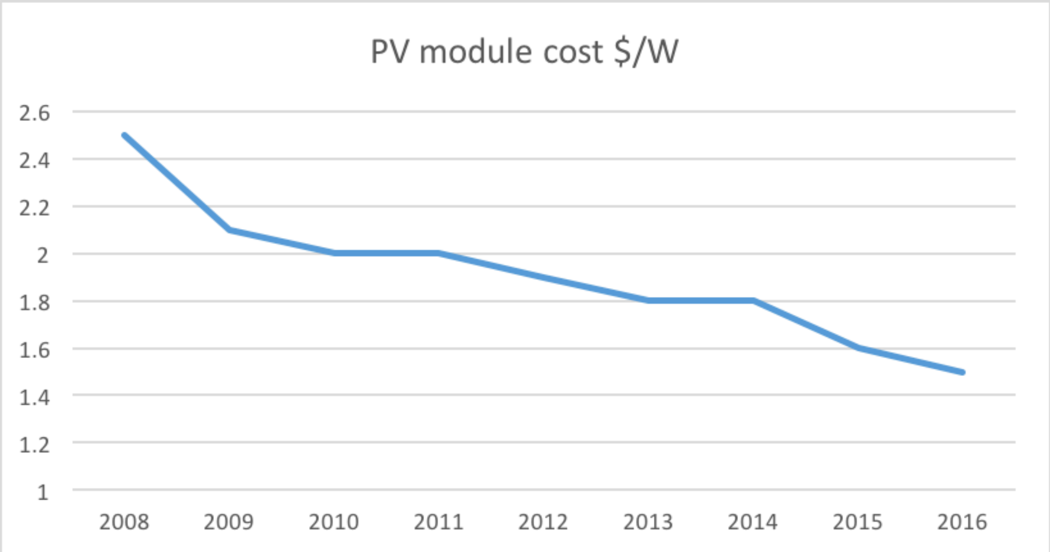

Figure 4.0: PV module cost projection (Parimita Mohanty, 2016).

PV cells generate more energy when installed to face direct sunlight. The cells are installed to maximize the physical and economic performance of the system at an angle directly facing the sun, this will depend on the location of installation (EIA , 2015).

PV systems structures are flexible, as they are modular, and can be scaled to match the need. They can supply electricity to areas with or without grid connection. They are quick to install and require little maintenance; most systems come with a 25 years warranty.

The major benefit of PV systems is that they harness energy from the sunlight which is free. PV arrays do not just provide sustainable energy, but can also operate autonomously without any noise disturbance. Unlike other means of renewable energy, they require minimal maintenance and running cost. They consist of no mechanically moving parts, hence minimizing any faults or breakage occurring.

2.4 Energy storage

Li – 120 lithium batteries have been chosen for this study because they are dependable and ideal for large commercial use. They are lithium-iron-manganese-phosphate that are of high grade, well mature technology, reliable, recyclable, have high cycle durability and require little maintenance. They are also scalable and can be connected in series.

2.4.1 Modeling of battery system

Since PV systems are not operational at night, which is one of the limitations of this technology, a battery system is used to store any daytime excess energy for use at night time. The size of the battery storage depends on the maximum discharge depth, battery capacity and temperature corrosion (Deshmukha, 2006).

The lifespan of the battery usually depends on the duration of usage. Most manufacturers normally give a warranty of 10 years or 10,000 cycles, whichever occurs soonest (Bre, 2016).

2.4.2 Types of storage

There are different batteries available in the market today, some are more matured than others designed to meet various unique requirments. The size, cost, lifespan, maintenance requirements and installations are some of the issues to consider when choosing a battery. For renewable energy storage, the most commonly used batteries are the lead acid, lithium-ion and flow batteries. (Solar Power World, 2016).

2.4.3 Cost of storage

The cost of battery storage varies with the size of the system, for the propose of this analysis, the lithium–ion battery system chosen will cost $1 million.

2.5 Hybrid energy system model

The hybrid system proposed in this study is the combination of PV and diesel generators that work in parallel. Hybrid energy systems provide a solution for the electrification of rural areas where there is little or no grid connection. The proposed model is designed to mitigate the limitation of PV and diesel generation when operated alone (Ashok, 2006). The hybrid system also needs an intelligent management system to ensure that the energy generated from the PV panels is used or stored as a function of the demand.

Basically the diesel genset complements the PV system, by matching demand during the night or at peak demand times. There is also an option of storing the excess energy harnessed from the PV into batteries, hence increasing the potentials of the PV system making them useful even at nights (Renewable energy world, 2016).

Figure 5.0 shows the configuration of the hybrid system comprising PV/diesel generation systems with battery storage.

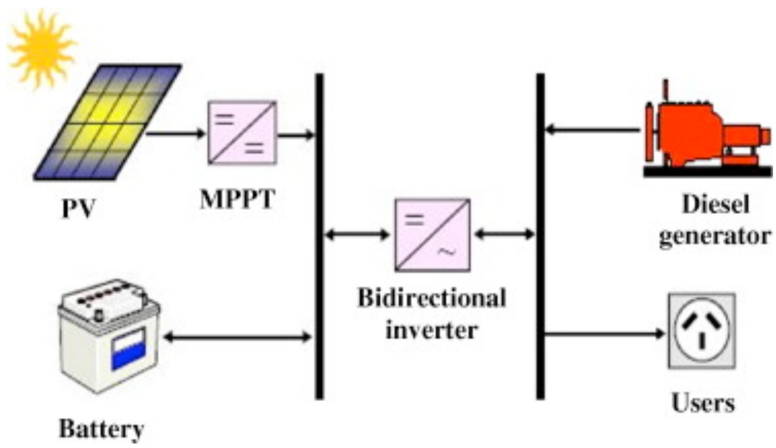

Figure 5.0 : Hybrid system configuration (Khelif, 2012).

Various hybrid renewable energy system modeling techiques exist. The method proposed by Deshmukha (2006) is used here.

2.6 Financial Appraisal.

The alternative systems were subjected to running, maintenance and capital cost analysis, with the economical evaluation based on the following assumptions.

1. That the repayment period for the loan is 25 years.
2. The maintenance cost is 3% of the capital cost, except for the diesel generator, which depends on the usage.

The following formula was used to calculate the annual loan repayment.

$$Yearly\ Repayment = \frac{Cr(1+r)^n}{(1+r)^n - 1}$$

where:

C is the capital loan

n the number of years to complete the repayment

r the rate of interest on the loan.

3 Case Study Description

Many Nigerians live in small towns and villages with an average population of 40,000. These towns and villages have poor grid connection and are heavily reliant on diesel generators, which only a very small percentage of the population can afford, while others use alternative means of energy such as oil lamps, firewood, candles, torches (batteries) and lanterns. The energy issues in these parts of the country reduce the standard of living, hence the government is eager to invest in a cost-effective and reliable energy system. These areas are well situation with no mountains obstructing direct sunlight.Agharha–Otor is an example of such a village, and is used as the case study in the present work.

As seen in figure 6, Agharha–Otor is a region north of Ughelli, Delta State, Nigeria. It is situated 263 miles south of the country capital Abuja, at latitude 5° 32' 5" North and longitude 6° 4' 29" East. It has a population of over 40,000. Like most rural areas in Nigeria, the majority of the residents live in abject poverty. Since energy usage affects our everyday lives, improving energy supply in this community will create more job opportunities for the population thus increasing the standard of living.

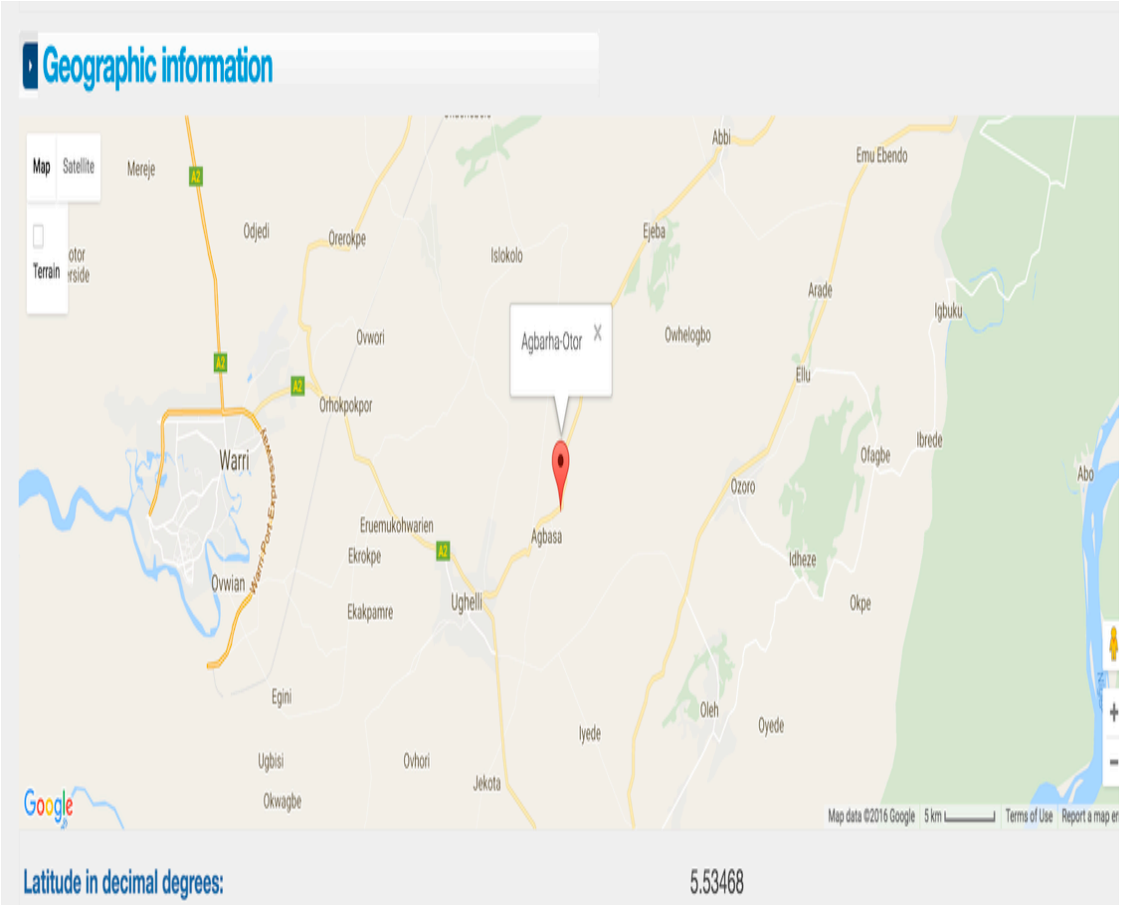

Figure 6.0: Map of Agharha–Otor (Google Map).

The sizing of the energy system is applicable to many small towns in Africa where the energy usage is for the purpose of electrification, cooking and cooling with no heating requirements due to the climate condition of these areas.

Table 3 shows the average monthly temperature of Agbarha –Otor (which is equivalent to the national monthly temperature).

Table 3: Solar radiation data.

Month	Daily horizontal solar radiation	Air temperature
	kWh/m²	°C
January	6.01	27.2
February	6.00	26.9
March	5.68	26.5

April	5.49	27.3
May	4.99	25.5
June	5.01	23.2
July	4.31	24.6
August	4.14	24.3
September	4.86	24.0
October	4.87	24.1
November	5.10	24.6
December	5.89	24.5
Annual	5.2	25.2

Table 4 compares the current prices of the technologies analyzed in this study.

Table 4: Present technologies pricing (Anayochukwu, 2013).

Item	Initial cost per W	Replacement cost	Maintenance cost (kW/y)
PV modules	$1.5/W	$1.2/W	$100/y
Diesel Generator 30kVA	$500,000	$500,000	$5/h
Converter	$1,500	$2/W	$100kW/y
Battery (optional)	$5000	$5000	$500

4.0 Financial Analysis

This Chapter examines the financial and economic analysis of the different energy systems selected in this thesis. A financial appraisal was conducted considering the economical parameters on the following technologies to determine the most cost-effective system for the considered community.

Option A: Diesel generator as standalone system

Option B: Autonomous PV system

Option C: PV system with energy storage

Option D: PV/diesel hybrid system

4.1 Scenario 1: Present day cost analysis

Option A (Diesel generator only):

This option consists of a standalone diesel generator system that has a full load capacity of 5 MW, providing a total energy consumption for this community of 3230 kWh. This means that the system is only required to operate at ¾ of its capacity. Table 5 shows the fuel consumption summary. The system will need 6218.4 gallons of diesel per day, this is a large amount of diesel consumption with a significant carbon dioxide emission.

The initial cost of this system for a 5 MW diesel generator is $1million, but a 2.5 MW diesel genset costs $325,000. Hence the study has opted for two 2.5 MW systems costing $650,000 in total, with an installation cost of $500,000 for both systems. Due to the high carbon dioxide emissions it was better to opt for two 2.5 MW units to allow ease of capacity regulation.

The cost analysis is as follows.

The annual repayments:

Where C is the capital loan given as $3,500,000. Cost of annual maintenance is assumed at $2,000,000 per year. This is expensive, but if the system is to be operated for 24 hours it will require constant maintenance.

The annual repayment cost of the system = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = \$3,500,000 + \$4,000,000 + \$2,000,000 + \$500,000 = \$10,000,000

Assuming a 25 years repayment period and 10% interest rate:

$$Annual\ Repayments = \frac{10{,}000{,}000 \times 0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$999{,}999$$

Assuming that the total energy cost for the community is \$2,000,000 per year:

The cost of energy$= \frac{Total\ \ cost\ \ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$999{,}999\ \times 100}{\$2000 \times 10^{3}} = 50 cents/kwh.$

Scenario 1A shows the total annual cost for a standalone diesel system operating for a 24 hours period to be the total of \$10 million and a \$1million annual repayment cost. Assuming that the community is taking a loan from the federal government for this system, with a repayment period of 25 year at 10% interest rate, the cost of energy will be 50 cent/kWh. This is quite expensive and unaffordable for a community of farmers and those living below the poverty line.

4.2 Scenario 1: Option B – PV solar panels

For a large installation of 4000 KW, with current price of PV solar panels, the capital cost is approximately \$4.8 million (The eco experts, n.d.), with a 10 year warranty. The installation cost for a large system like this will be about \$3 million. This technology also requires the use of an inverter to function; this is used to convert the output from DC to AC that is then fed into the grid (Wikipedia, 2016). Thus, the cost of an inverter is also considered in the cost analysis. A micro-inverter is the latest in the market today, has a long life span and requires little or no maintenance. They come with a 25 year warranty. The average cost for 4000 KW solar panel system will be \$1million (The eco experts, n.d.). Hence, the total initial cost for this technology comes to \$8 million. The financial calculation for this option is as follows.

Due to the low maintenance requirement for the system, the maintenance cost is calculated at 3% of the initial value of the system.

Cost of annual maintenance of 3% of the total cost = $0.03 \times 8.0 \times 10^6 = \$240{,}000$

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = \$8,000,000 + \$0 + \$240,000 + \$1,000,000 = \$9,240,000

$$Annual\ Repayments = \frac{9{,}240{,}000 \times 0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$923{,}999$$

Again, assuming the cost of energy for the community is \$2 million per year.

The cost of energy= $\frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$923{,}999 \times 100}{2 \times 10^6} = 46.2\ cents/kWh$.

Scenario 1B consists of a PV panel system as a standalone system; it is a renewable means of energy generation. The free and abundant solar energy being the sole source of this scenario, hence it has zero operational cost. Table 2.2 shows a gradual decline in the prices of PV system over the years, but for a large installation it would still cost as much as \$8 million (including the cost of inverters) to generate over 4000 kWh of electricity. With installation and maintenance costs, the total annual borrowing needed is \$9,264,000 with an annual repayment of \$926,999. Once more, assuming a 25-year repayment and 10 % interest rate the electricity could be sold for 46.2 cent/kwh. Although this system is cheaper than option A, it is still not affordable for the community. Moreover, this technology is not very feasible as it is unreliable when operated autonomously.

4.3 Scenario 1: Option C – PV System with energy storage

This system consists of the PV system of scenario B, but with a battery to store excess energy that could be used at night. The battery system makes the PV panels more efficient by bridging the gap between periods of generation and period of consumption. These are scalable and modular storage systems designed for large commercial uses, they come with 10 years performance warranty. The initial cost of this system for the required energy target is assumed at $1.7 million. This brings the total cost of this scenario to $10.5 million. The installation of the battery system is assumed to cost $500,000. Therefore the total installation cost for this scenario will be:

Total installation cost of PV panels + Battery cost = $3,000,000 + $500,000

Total installation cost = $3.5 million.

The battery system requires little maintenance; for the size of the battery system required, the maintenance has been assumed to be $66,000. From this information the annual loan repayment is calculated as follows:

Cost of Annual Maintenance at 3% of the total cost of the system $= 0.03 \times 8.0 \times 10^6 = \$240{,}000$

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = $9,000,000 + $0 + $306,000 + $1,200,000 = 10,506,000

$$Annual\ Repayments = \frac{10{,}506{,}000 \times 0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$1{,}050{,}599$$

Again, assuming the cost of energy for the community being $2 million per year.

The cost of energy$= \frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$1{,}050{,}599 \times 100}{2 \times 10^6} = 52.5\ cents/kwh$.

Option C (PV system with energy storage) adds battery storage to option B. Due to the limitation of the PV system a battery storage system will make this system more feasible, as it makes he captured energy useful at night when there is no sunshine. The addition of a battery system in this scenario makes the total capital cost expensive. This scenario requires $10.5 million to design, assuming a repayment of 25 years and 10% interest rate the yearly repayment is over $1 million. It will make the cost of energy 52.5 cent/kwh, meaning that the community will have to pay 6.3 cents/kWh more to install the battery storage and make this system more reliable and dependable.

4.4 Scenario 1: Option D – PV/ diesel hybrid system

Here, the PV system works with the diesel generator in parallel or the diesel system serves as a backup energy system. The initial cost used for analyzing this scenario is the total initial cost of PV system and diesel system. The maintenance cost of the diesel generator is cheaper in this scenario as the diesel generator is only operated as a backup or only at night times.

The loan repayment for this scenario could be calculated as follows:

Capital cost = initial cost of PV + initial cost of diesel generator set = \$8,000,000 + \$3,500,000 = \$11,500,000

Operational cost = running cost for PV + ½ day running cost of diesel system = \$2,000,000 = 0 + \$2,000,000 = \$2,000,000

There is a 50% savings in the annual maintenance cost of the diesel system in this option, as the system is only operated half a day instead of the full day calculated in option A. The yearly energy demand for a typical area like the case study has an average annual energy requirement like figure 3. Figure 3 shows that the maximum load required is in March, April, May, June and December according to literature review.

Annual maintenance cost: PV maintenance cost + ½ diesel maintenance cost = \$1,264,000

Total installation cost: PV Installation cost + diesel installation cost = 1,000,000 + 500, 000 =\$1,500,000

Hence, the total annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = \$11,500,000 + \$2,000,000 + \$1,264,000 + \$1,500,000 = \$16,264,000

$$Annual\ Repayments = \frac{16{,}264{,}000 \times 0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$1{,}626{,}399$$

Again, assuming that the energy cost per year is valued at \$2 million.

The cost of energy= $\frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$1{,}626{,}399\times 100}{2\times 10^6} = 81.3\ cents/kwh.$

Option D (PV/diesel hybrid system) is the ideal scenario, it consists of a hybrid energy system of PV/ diesel generator system. The system proposed in this scenario is designed to work either in parallel or to complement each other. The diesel system could be brought on in times of peak demand or just at night. Since the diesel system is only operated at half the initial period there is a 50% savings in the maintenance cost, but the operational cost of the diesel generator and the initial cost of the PV system makes this scenario the most expensive. It will require a borrowing of over $16.2 million to design the system. The yearly repayment will cost over $1.6 million and the energy cost of 81.3 cent/kwh.

Table 5 shows that option A has the lowest initial and installation costs of the system but has the highest maintenance cost due to the length of operation. Although this technology is reliable, it requires a huge operational cost and also generates noise and air pollution. Option D is the most expensive technology as can be seen in Table 5, but cheaper to operate compared to option A.

Table 5.0: Present cost analysis

Scenarios 1 (Energy options)	Initial cost ($)	Running cost/annum ($)	Maintenance cost/annum ($)	Total Annual cost ($)
Option A – (Diesel generator)	3,500,000	4,000,000	2,000,000	10,000,000
Option B- (Autonomous PV)	8,000,000	0	264,000	9,264,000
Option C (PV + battery)	9,000,000	0	306,000	10,506,000
Option D – (Diesel + PV)	11,500,000	2,000,000	1,264,000	16,264,000

4.5 Scenario 2 – Futuristic analysis

This scenario is based on future prices with the assumption that the cost of all technologies is half their present value. The same study as above is carried out to discover if this reduction in the cost of the technology makes the system cost-effective. The scenario is also divided into option A (diesel generator as standalone), option B (autonomous PV system), option C (PV system with storage), and option D (PV /diesel hybrid system). The loan repayment calculations are repeated for each energy option for this scenario. All calculation for scenario 2 can be found in appendix A, and their cost analysis table can be found on appendix D.

4.6 Scenario 3 - Futuristic cost + government subsidy

This is a futuristic price analysis with the addition of a government subsidy and at reduced interest rate. This scenario is based on the community been granted a 50% subsidy by the Nigerian government. The maintenance rate is reduced from 3% to 1% of the initial cost and the interest is also reduced from 10% to 1% (90% reduction) thus making the annual loan repayment more affordable by the community, which in turn makes the prices of energy more affordable. The scenario is also divided into four energy options: option A is a diesel generator operated in standalone mode, option B is an autonomous PV system, option C is a PV system with energy storage, and option D is a PV/diesel hybrid system. The calculation for scenario 3 can be found in appendix E.

Figure 7 shows that the most expensive technology is option D from scenario 1, which is the hybrid energy system that consists of the PV/diesel system. This is due to the operation cost and high capital cost of a hybrid system.

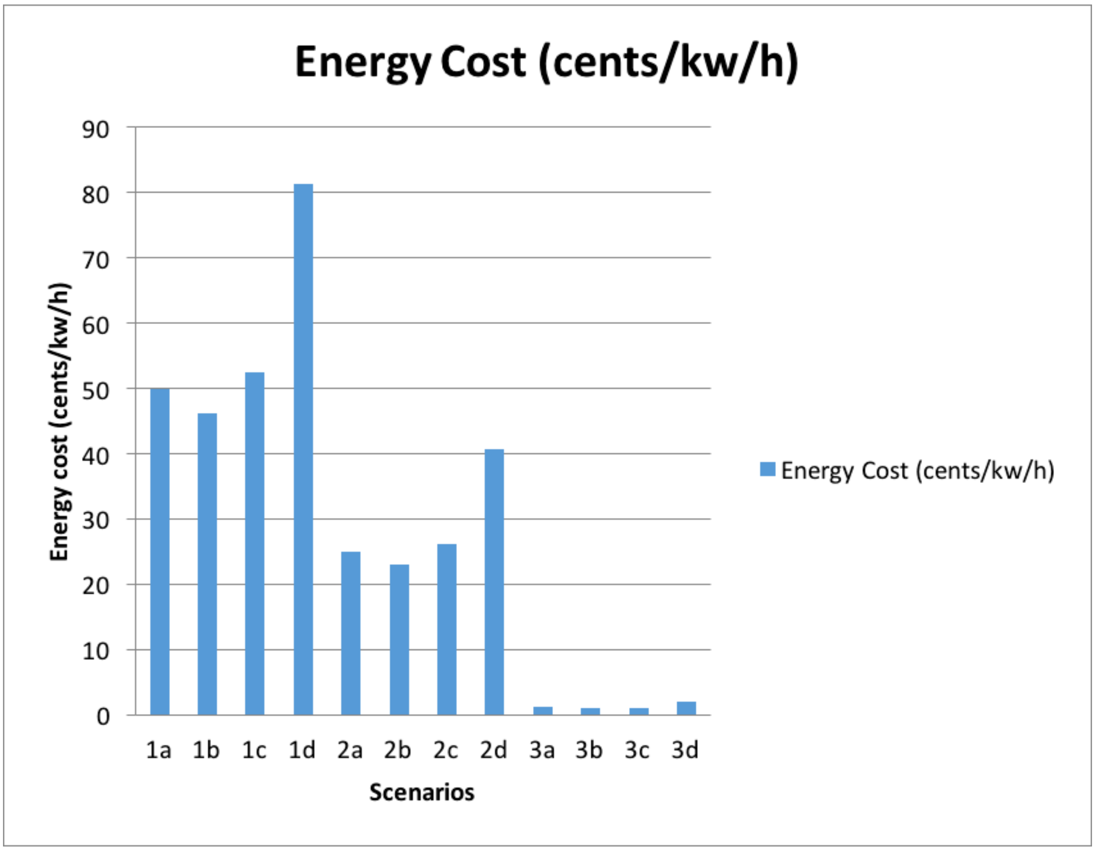

Figure 7.0: Scenario energy cost comparison

Table 6 shows the environmental impact and the reliability assessment of each of the technology options. This is rated from 1 to 5 for the environment assessment, with 1 being the least polluting and 5 the most polluting source of energy. The reliability assessment is also rated from 1 to 5, with 1 being the least reliable and 5 the most reliable technology.

Option A, the diesel only systems, is the most polluting source with large carbon dioxide emission; hence it is rated 5 although the system is reliable. If operated for 24 hours as proposed this will have an impact in the efficiency and reliability of the system, reducing the rating to 4 on reliability. Option B is the cleanest means of energy generation, but it is unreliable due to its operational constraint, therefore it is rated 1 both on environmental impact and reliability. Option C, a PV system with battery storage, is rated 2 on both environmental impact and reliability: although PV is clean technology batteries are less so much; conversely the system is more reliable with energy storage. Option D, the diesel/ PV hybrid system, is rated 3 on environmental impact, which is average, and 5 on reliability making this option the most reliable system option in this study.

Table 6: Energy option environmental impact and reliability assessment.

Energy options	Environmental impact	Reliability
Option A – (Diesel generator)	5	4
Option B- (Autonomous PV)	1	1
Option C (PV + battery)	2	2
Option D (Diesel/ PV)	3	5

5.0 Conclusions and Future Work

The most dependable, suitable and cost-effective technology was chosen for a typical community based on the capital, maintenance and running costs corresponding to alternative system configurations:

- Diesel generator as standalone system
- Autonomous PV system
- PV system with storage
- PV/diesel hybrid system.

In a rural community where 90% of the population live below the poverty line, as in most African rural areas, from the calculations and analysis the only way these communities can have a reliable and stable energy supply is when the conditions of scenario 3 are met. As shown in in figure 4, any of the technology options in scenario 3 are cost-effective and affordable by the community, meaning that the only way this community can afford low cost energy supply is with the help of the Nigerian government. Since the country aims to reduce its carbon emissions by 50% by 2030, it should look towards investing more into renewable means of energy generation. Therefore, the future work will be for the community to look into other means of renewable energy system such as wind energy generation, which can generated energy both at night and during the day, and can also run autonomously. The community could also consider modeling a hybrid system of wind turbine/ PV, and with adequate storage system, this could prove to be a very reliable, efficient and cost-effective means of providing energy to these areas. This type of system will be costly under he present market conditions but could be more affordable in future.

An environmental and reliability assessment of the different energy options was undertaken so that an informed decision could be made about which system best serves the community. Option D, the hybrid system, is not just the most reliable system, but also has an average rating on environmental impact assessment making it the ideal energy system for the community.

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Appendix – A (SCENARIO 2 – Futuristic scenario)

Scenario 2 shows the futuristic scenario with 50% price reduction as shown in Table 6 compared with the present prices. This scenario is designed with the following assumptions:

- The price of diesel is half the current price
- The initial prices of the technologies are half their current prices.

For scenario 2: Option A (Diesel generator only)

The cost analysis is as follows:

The annual repayments

Where C is the capital loan given as $1,750,000. Cost of Annual Maintenance of this system is assumed at $1,000,000 per year. This is quite expensive, but if the system is to be operated 24 hours it will require constant maintenance.

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = $1,750,000 + $2,000,000 + $1,000,000 + $250,000 = $5,000,000

Assuming a 25 years repayment period and 10% interest rate.

r is the rate of interest on the loan 10% = 0.1

$$Annual\ Repayments = \frac{5{,}000{,}000 \times 0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$499{,}999$$

Assuming that the total energy cost for the community is $2,000,000 per year.

The cost of energy= $\frac{Total\ \ cost\ \ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$499{,}999\ \times 100}{\$2000 \times 10^3} = 25 cents/kwh.$

For Scenario 2: Option B (Autonomous PV only)

Due to the low maintenance requirement for the system, the maintenance cost is calculated at 3% the initial value of the system.
Cost of Annual Maintenance of 3% of the Total cost = $0.03{\times}4.0{\times}10^{6}$ = $\$120{,}000$

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = $4,000,000 + $0 + $120,000 + $500,000 = $4,620,000

$$Annual\ Repayments = \frac{4{,}620{,}000{\times}0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$461{,}999$$

Again, assuming the cost of energy for the community is $ 2 million per year.
The cost of energy= $\frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$461{,}999{\times}100}{2{\times}10^{6}} = 23.1\ cents/kwh$.

For Scenario 2: Option C (PV + Battery)

This energy system is similar to the option B, but with the addition of a battery system.
Cost of Annual Maintenance of 3% of the Total cost of the system $= 0.03{\times}4.0{\times}10^{6} = \$120{,}000$

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = $4,500,000 + $0 + $153,000 + $600,000 = 5,253,000

$$Annual\ Repayments = \frac{10{,}506{,}000{\times}0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$525{,}299$$

Again, assuming that the cost of energy for the community is $ 2 million per year.
The cost of energy= $\frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$525{,}299{\times}100}{2{\times}10^{6}} = 26.25\ cents/kwh$.

For Scenario 2: Option D (PV + diesel generator hybrid system)

Capital cost = initial cost of PV + initial cost of diesel generator set = \$4,000,000 + \$1,750,000 = \$5,750,000

Operational cost = running cost for PV + ½ day running cost of diesel system (since the diesel is operating only half a day) = \$1,000,000 = 0 + \$1,000,000 = \$1,000,000

There is a 50% savings in annual maintenance cost of the diesel system in this option as the systems is only operated half a day instead of the full day calculated in scenario 1 option A.
Annual maintenance cost: PV maintenance cost + ½ diesel maintenance cost = \$620,000

Total installation cost: PV Installation cost + diesel installation cost = 500,000 + 250, 000 =\$750,000
Therefore, the total annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = \$5,750,000 + \$1,000,000 + \$620,000 + \$750,000 = \$8,120,000

$$Annual\ Repayments = \frac{8{,}120{,}000 \times 0.1(1+0.1)^{25}}{(1+0.1)^{25}-1} = \$813{,}199$$

Again, assuming that the energy cost per year is valued at \$2 million.

The cost of energy= $\frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$813{,}199 \times 100}{2 \times 10^6} = 40.65\ cents/kwh.$

Appendix B – (Scenario 3 – Futuristic prices + government subsidy + reduced interest)

This scenario is a combination of futuristic scenario with the addition of government subsidy. These scenario is based on the following assumptions.

- All costs as based on futuristic cost (50% reduction from present cost)
- The government is to grant the community a subsidy to cover 50% of the total yearly cost of the technology.
- The interest rate is to be reduced from 10% to 1% over the 25 years repayment period.
- The maintenance cost is only 1% the initial cost.

For scenario 3: Option A (Diesel generator only)

The cost analysis is as follows:
The annual repayments

Where C is the capital loan given as $1,750,000. Cost of Annual Maintenance of this system is assumed at $1,000,000 per year. This is quite expensive, but if the system is to be operated for 24 hours it will require constant maintenance.

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = $1,750,000 + $2,000,000 + $1,000,000 + $250,000 = $5,000,000.
Since the government is granting the community a 50 % subsidy towards the cost of the technology the community is only paying half the cost of the technology, which is $2,500,000. Assuming a 25 years repayment period and 1% interest rate.

r is the rate of interest on the loan 1% = 0.01

$$Annual\ Repayments = \frac{2{,}500{,}000 \times 0.01(1+0.01)^{25}}{(1+0.01)^{25}-1} = \$24{,}999$$

Assuming that the total energy cost for the community is $2,000,000 per year.

The cost of energy= $\frac{Total\ \ cost\ \ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$24{,}999\ \times 100}{\$2000\times 10^{3}} = 1.25 cents/kwh.$

For Scenario 3: Option B (Autonomous PV system)

Due to the low maintenance requirement for this system, the maintenance cost is calculated at 1% the initial value of the system.

Cost of Annual Maintenance of 1% of the Total cost $= 0.01\times 4.0\times 10^{6}\ = \$40{,}000$

The annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = $4,000,000 + $0 + $40,000 + $500,000 = $4,540,000.

Again, due to the 50% cost subsidy by the government the community is only responsibility for half the annual cost of the technology, which is $2,270,000 in this case.

$$Annual\ Repayments = \frac{2{,}270{,}000\times 0.01(1+0.01)^{25}}{(1+0.01)^{25}-1} = \$22{,}699$$

Again, assuming that the cost of energy for the community is $ 2 million per year.

The cost of energy= $\frac{Total\ \ cost\ \ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{22{,}699\times 100}{2\times 10^{6}} = 1.13\ cents/kwh.$

For Scenario 3: Option C (PV + Battery)

This system is similar to the option B, but with the addition of a battery system.

Cost of Annual Maintenance of 1% of the Total cost of the system $= 0.01\times 4.5\times 10^{6} = \$45{,}000$

The annual repayment cost of the system is= Capital cost + Operational cost + Annual Maintenance cost + Installation cost = \$4,500,000 + \$0 + \$153,000 + \$45,000 = 4,698,000

Therefore half the annual cost is \$2,349,000

$$Annual\ Repayments = \frac{2{,}349{,}000 \times 0.01(1+0.01)^{25}}{(1+0.01)^{25}-1} = \$23{,}489$$

Again, assuming that the cost of energy for the community is \$ 2 million per year.

The cost of energy= $\frac{Total\ cost\ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$23{,}489 \times 100}{2 \times 10^{6}} = 1.17\ cents/kwh$.

For Scenario 3: Option D (PV + Diesel Generator)

Capital cost = initial cost of PV + initial cost of diesel generator set = \$4,000,000 + \$1,750,000 = \$5,750,000.

Operational cost = running cost for PV + ½ day running cost of diesel system (since the diesel is operating only half a day) = \$1,000,000 = 0 + \$1,000,000 = \$1,000,000.

Annual maintenance cost: PV maintenance cost + ½ diesel maintenance cost

PV Annual maintenance at 1% the initial cost = \$40, 000

Diesel generator annual maintenance 50% discount due to half a day operation = \$500,000

Total maintenance cost for both technologies: \$540,000

Total installation cost: PV Installation cost + diesel installation cost = 500,000 + 250, 000 =\$750,000

Thus, the total annual repayment cost of the system is = Capital cost + Operational cost + Annual Maintenance cost + Installation cost = \$5,750,000 + \$1,000,000 + \$540,000 + \$750,000 = \$8,040,000

Due to the government subsidy the annual cost is half; hence the community is only responsible for 50% of the annual cost which is now \$4,020,000

$$Annual\ Repayments = \frac{4{,}020{,}000 \times 0.01(1 + 0.01)^{25}}{(1 + 0.01)^{25} - 1} = \$40{,}199$$

Assuming that the energy cost per year is valued at $2 million.

The cost of energy= $\frac{Total\ \ cost\ \ per\ year}{Total\ Energy\ cost\ per\ year} = \frac{\$40{,}199 \times 100}{2 \times 10^{6}} = 2.0 cents/kwh$.

From the analysis only scenario 3 was cost effective and affordable, and the most cost effective under this scenario is option B which cost 1.13 cent/kw/h.

Appendix C – Mathematical model of PV system (www.PV software.com)

Mathematical model of the solar PV energy output

(yellow)	Yellow cell = Data can be modified
(green)	Green cell = Data can be modified
(white)	White cell = calculated value (do not change the value)

Global formula : E = A * r * H * PR

E = Energy (kWh)	3230	kWh/an
A = Total solar panel Area (m²)	20	m²
r = solar panel yield (%)	20%	
H = Annual average irradiation on tilted panels (shadings not included)*	1250	kWh/m².an
PR = Performance ratio, coefficient for losses (range between 0.9 and 0.5, default value = 0.75)	0.75	

Total power of the system	3.0	kWp

Losses details (depend of site, technology, and sizing of the system)

- Inverter losses (6% to 15 %)	9%
- Temperature losses (5% to 15%)	9%
- DC cables losses (1 to 3 %)	3%
- AC cables losses (1 to 3 %)	3%
- Shadings 0 % to 40% (depends of site)	4%
- Losses weak irradiation 3% yo 7%	4%
- Losses due to dust, snow... (2%)	2%
- Other Losses	0%

Appendix D – scenario 2: Futuristic cost analysis Table

Energy options	Initial cost ($)	Running cost/annum ($)	Maintenance cost/annum ($)	Total Annual cost ($)
Option A – (Diesel generator)	1,500,000	2,000,000	500,000	2,000,000
Option B- (Autonomous PV)	4,000,000	0	264,000	4,264,000
Option C (PV + battery)	3,000,000	0	306,000	10,506,000
Option D – (Diesel + PV)	7,500,000	1,000,000	564,000	8,264,000

Appendix E – Fuel consumption mathematical model

	Fuel consumption (gallons)			
Load Capacity(5MW)	6 hours	12 hours	18 hours	24 hours
½	1036.8	2073.6	3110.4	4147.7
¾	1554.6	3109.2	4663.8	6218.4
Full	2073	4141.2	6211.8	8282.4