An Appraisal of Solar Powered Water System for Sustainable Rural Development

Makinde Kayode[1], Man Alhaji Sulaiman[2], Ibrahim Abubakar[3], Amao Enock[4]
[1,2,3]*Department of Electrical Engineering, Federal Polytechnic Bida, Niger State, Nigeria*
[4]*Department of Physics, Federal Polytechnic Bida, Niger State, Nigeria*

Abstract: - **In locations where electricity is unavailable, other means are necessary to pump water for consumption. Solar photovoltaic is strongly proven for cutting down greenhouse gases emissions, cost of fuel (diesel) and environmental pollution problems that the world is facing today due to the use of non-renewable energy sources. Niger state considered in this study is also experiencing these challenges with imbalance and unreliable electrical power supply. The case chosen was Gubata village in Gbako local government, Niger State. The purpose of this paper is to investigate the potentiality and cost effectiveness of using solar borehole system in Gubata Village in Gbako local government area in Niger State. The Analysis of the solar powered system was based on the estimated daily water supply rate of 40,000 litres. A cost-comparison analysis between the solar-powered system and generator powered system was done using Life-Cycle Costing Analysis. Results obtained from the study showed that a 1.4 kW solar powered unit can supply the desired water quantity. Comparing the power supply costs of both systems over a 5-year life cycle showed that the diesel-generator powered system has a present value cost of about 230% higher than that of the solar powered unit. The outcome of this study showed that the PV pumping systems include low operating cost, unattended operation, low maintenance, easy installation, and long life.**

Keywords: **Solar Power System, Solar Pump, Design, Motorised pump, Rural areas, Sustainability, Cost Benefit Analysis**

I. INTRODUCTION

Energy is key to sustainable development of any communities. It is also intrinsic to meeting the developmental needs of more than 1.2 billion people worldwide living under extreme poverty. Electricity, for instance, is an indispensable input for productive and economic activities, as well as for overall health and well-being of communities (Deen, 2014).

However, expanding access to electricity services is an enormous challenge for developing countries like Nigeria.

Globally people still lack access to safe water, despite the Millennium Development Goal (MDG) target for water being met. Even when improved drinking water sources exist, ensuring safe and sustained water services remains a challenge. Over the past few years, United Nations Children's Fund (UNICEF) has been exploring new and innovative approaches to water supply, placing an emphasis on systems which are affordable, scalable, and environmentally sustainable and climate smart. Solar powered water systems have the potential to meet all of these criteria (UNICEF, 2016)

A solar water pumping system is ideal in remote locations where grid electricity does not exist or it is cumbersome to use gasoline or diesel to feed a pump. There are very distinct differences between the two power sources in terms of cost and reliability. Diesel pumps are typically characterized by a low initial cost but very high operation and maintenance cost. On the contrary, solar has high initial cost but very low operational and maintenance costs. Solar pumping has had clear advantages for a number of years but the differences are becoming more striking in a world of rapidly escalating fuel costs. Not only will some of the world's poorest people not be able to afford fuel for their pumps, but living at the end of remote supply chains, they may not even be able to get it in the first place as world demand overtakes supply (SELF, 2008)

II. AIM AND OBJECTIVE

The purpose of this research is to compare the cost of solar powered pump over diesel powered pump in Nigeria rural communities. The general objective of this study is to design and implement a solar photovoltaic (PV) powered water supply system for rural areas in Nigeria using Gubata Village in Gbako Local government without electric grid connection as a case study.

III. METHODOLOGY

In designing a Solar Pumping System, there are many guides involved in the design. This guide provides the information to correctly select a pump, sensors, solar array, wiring, and pipe. The method adopted in this study is purely analytical. The device was design using mathematical analysis and was converted into experiment by following the design results obtained in procuring the needed materials for the design.

Description of Study Location

Gubata is a village in Gbako local government area of Niger state in Nigeria (plate 2 (a). It is located in about 7 kilometers away from Bida along Pichi. The community is of a rural setting with a population of about 2000. The villagers engage in farming for subsistence as well as commercial farming and depend on water from a stream for washing, drinking, bathing, and cooking. World Health Organisation (WHO) postulated that on an average; 20 litres of water is sufficient for one person per day. Therefore, daily water consumption in Gubata village for 2000 people will be about 40,000 litres per day. Being within 7 kilometers radius from Bida city centre, the average daily insolation values for Bida was used for this design. Table 1 shows the average insolation values on a monthly basis over a period of 18 months.

Table I. Monthly Insolation values of Bida (Measured in $kWh/m^2/day$ onto horizontal surface, January 2016 –June 2017). Source: Mico weather, 2017 Daily weather forecast powered by Amber weather forecast.

JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC
6.7	3.2	6.3	8.9	6.8	4.1	4.5	3.9	5.5	7.0	7.9	6.8
7.2	5.5	8.3	7.1	6.5	6.2						

From the Table I, the average solar irradiance for this period of 18 months was estimated to be 6.2 $kWh/m^2/day$ and this was used in the design of the solar powered supply system.

Estimation of Water Supply Rate

The hourly water output of the system which is essential to pump the required water was calculated using the daily water supply capacity of the system and the daily sun hours. The daily sun hours is a value derived from the average daily solar irradiance in Bida.

The formula used in calculating the daily flow rate is given as;

$$\text{Daily Flow Rate} = \frac{\text{System water supply capacity}}{\text{Average daily Insolation}} \quad \text{(Nwobi 2014)} \qquad (1)$$

Since about 2000 people is assumed to be the total population of the village (Shiru, personal communication, 21/07/2018), the total daily water supply will be 2000 x 20 (WHO, 2011) that's 40,000 ltrs/day. Hence the borehole will be designed to produce a minimum of 40000 litres /day ($40m^3/day$) of water daily.

Recall from table 1; the average sun hours per day in Bida was given as $6.2kwh/m^2/hour$

$$\text{And Hourly Flow Rate} = \frac{40}{6.2} = 6.5\text{m}^3\ /\text{hour}$$

Therefore, Daily hydraulic load was calculated to be 1000 m^4/day. The formula reported by NAMREP (2006) was used and is given as;

Daily hydraulic load [m^4/day] = daily flowrate [m^3/h] x head (m) (NAMREP,2006) (2)

Daily hydraulic load [m^4/day] = 6.5 x 120 = $780m^4/day$ nearest pump size is1000 m^4/day

Pumps with Hydraulic load of 1000 m^4/day i.e $6.5m^3/day$ Grundfos SQ Flex (1400) is suitable for usage (www.groundfos.com)

Therefore, SQ Flex (1400) was used for the work.

Sizing

In order to create a basis for comparison between PVPs and DPs the performance of the pumping options are linked to dedicated delivery heads as it is provided by the manufacture (www.groundfos.com).

Throughout the study the delivery of the PV pump system is based on the daily delivery whereas the diesel pump system is based on the hourly flowrate. To compare PVP and DP at a particular head a daily delivery is used. While PVP delivery is daily, DPs operate at higher delivery rates for less hours so the daily flowrate is converted to an hourly flowrate for DPs. The sizing of the PVP systems is based on the performance charts provided by the manufacturers. The solar irradiation levels of 6.2kWh/m2/day has been used. This values falls with the allowable range provided by the manufacturer (i.e between 5 and 7kWh/m2/day), which is a representative average of Bida solar irradiance. Therefore 1,400Wpeak solar was

used as it was provide in the manufacture charts with a dc input of 30-300VDC at operating current of 8A.

$Installed\ Solar\ Panel\ Power = Required\ Power \times 1.25$ (Nwobi, 2014) (3)

It should be noted that the pump size is 1400W (plate 1) which means required power is 1400W

Plate 1: Pictorial view of the 1400W solar pump

Therefore, Installed Solar Power = 1400 x 1.25 = 1750W. it was observed that this combination will yield odd arrangement, so 2000W was chosen instead, which is even (4pcs for each pair). While selecting the solar panels (figure 1), a higher voltage system was preferred in order to reduce energy losses and cost of bigger wire sizes which accompany higher current systems. To achieve this, solar panels which normally come in voltage ratings of 24volts were connected in series to obtain this higher voltage and a reduced current. The total system voltage and power are given by

Figure 1: Photovoltaic (PV) panels

$Total\ SystemVoltage$ (Volts) = $V_1 + V_2 + V_3 + \ldots\ldots\ldots\ldots + V_n$ (4)

$Total\ System$ Power (Watts) = $P_1 + P_2 + P_3 + \ldots\ldots\ldots\ldots + P_n$ (5)

Where; n = number of solar panels in the array, V= Maximum voltage rating of each panel, P= Rated power output of each panel. Also the maximum current of the array was calculated thus;

$$\text{Maximum current of the array} = \frac{\text{Total Power of the array}}{\text{Total Voltage of the array}} \quad (6)$$

So from equation 4 and 5, n = total number of panels in array, here four panels was chosen for one array. Therefore n = 4, each of 250W/24V.

Total system voltage = 24 + 24 + 24 + 24 = 96V

Total system power = 250 + 250 + 250 + 250 =1000W

In this design, two strings of the 1000W was used. This means that, the two strings (2 separate arrays) of the solar panels were connected in parallel, the total power will be (1000 W + 1000W) which amount to 2000W. Invariably the total power, P_T = 2000W which is in conformity with calculated Installed Solar Power for the Pump.

It should be noted that the voltage range from 30 – 300VDC, in that case the range of voltage chosen determines the output power to drive the pump as specified by the manufacturer.

The maximum current of the array was calculated thus;

Maximum current of the array = 2000/96 = 20.83A

The minimum current to the pump is 8.4A, therefore, the panel will conveniently provide enough current both at the low and peak solar irradiance as it has excess of 12.43A.

Diesel Pump

Using a diesel generator for this system, it is rational to reduce the operational hours per day in order to prolong the life of the generator and to have a practical system. For this design, the storage capacity is 40,000 litres, which is the storage of water use for the system, since the power supply, unlike the solar powered system, is available on demand. The operational hours was scaled down to five hours which implies a higher pumping rate and a pump with higher power rating. An alternating current (AC) pump was used for this system and this imposes another additional power requirement for the motor starting current. Sizing a generator to meet the power needs of an AC pump requires that the power supply from the generator must be sufficient to provide the higher starting current drawn by the pump's AC motor during start-up. This current varies between 2 to 3 times the normal running current. Due to various start-up systems which tends to reduce this in-rush current, typical AC motor start-up power requirements are within 2 times the nominal power of the motor (Nwobi, 2014).

In this design, 5hours of daily pumping was assumed; therefore the new hourly rate is calculated thus;

Hourly rate = $40m^3/5 = 8\ m^3/h$

The new hourly rate is thus 8 m^3 / hour; this value was used to estimate the hydraulic power.

The diesel pump is sized by calculating the actual power required to lift water, i.e.:

$$HE = \frac{Q \times H \times \rho w \times g}{3.6 \times 10^6} \text{ (Abu – Aligah M., 2011)} \quad (7)$$

Or Hydraulic power [W] = ρ x g x head x flow (NAMREP, 2006) (8)

where

ρ = density of water [kg/m^3]

flow = flowrate [m^3/s] = m^3/(60x60)

ρw = density of water [kg/m^3] = 1000kg/m^3

g = gravitational acceleration [m/s^2] = 9.82$m/^2$

head (H) = total dynamic head [meters] = 120m

Q = hourly flow rate [m^3/h] = 8 m^3 / h

HE = hydraulic energy (kW)

Using both equations (7 and 8)

The result is;

= (1000 x 9.82 x 8 x 120) / (3.6 x 10^6) = 2.62kW (equation 7)

= (1000 x 9.82 x 120 x 8)/(3600) = 2.62kW (equation 8)

The hydraulic power required to pump 40000 litres of water in 5 hours is approximately 2.62kW.

Thus a pump rated at 2.62 kW (about 3.51 hp) is required for the system. For ease of procurement, a 3.5 hp pump was used for this system. The generator for this system is rated at 2 times the nominal power of the pump. Hence:

$Generator\ power$ = 2×3.5 (7hp) = 5.24 kW

Considering the mechanical loses, a 5.8 kW diesel generator was used to supply the energy required by this system.

IV. LIFE CYCLE COST COMPARISON FOR THE SOLAR AND GENERATOR POWERED SYSTEM

In order to compare different systems offering the same service/output the life cycle costing approach is used. This approach allows systems to be compared on an equal basis by reducing all future costs, which occur at different intervals of the systems life, to one value, referred to as the Life Cycle Cost (LCC) of a system/project. Future costs include operating costs (diesel consumption and transport), maintenance costs (engine oil, filters, brushes, diaphragms, valves, rotor, impellers, labour, transport, see table 2 for details) and replacements (diesel engine, motor, labour and transport, see table 2 for details

The Life cycle period of 5 years was considered in this design so that pump, generator and solar replacement will not occur within that period

The equation for the Life Cycle Cost Analysis of these two systems is thus: $Life\ Cycle\ Cost$ (LCC) =Cic+Ce+Cm+$Cenv$+Cr (9)

Where:

Cic= Initial costs, purchase price (pump, system, pipe, auxiliary services)

Ce= Energy costs (predicted cost for system operation)

Cm = Maintenance and repair costs (routine and predicted repairs)

$Cenv$= Environmental costs (contamination from pumped liquid and auxiliary equipment)

Cr=$Replacement\ Costs$.

Table II: Maintenance and Replacement Interval for Diesel Engine (SELF, 2008: Cost Reliability Comparison between Solar Powered and Diesel Powered Pumps)

Maintenance and Replacement	Low quality engine (hours)	Equivalent number of days
Minor service (engine oil, filters, transport)	250	50
Major service (brushes, decarbonisation, engine oil, transport, labour)	1,000	200
Overhaul (diaphragms, valves, rotor, impeller, drilling of cylinder, labour, transport)	5,000	1,000
Replacements (diesel engine, pump, motor, labour, transport)	10,000	2,000

Table III and table IV are the detailed analysis for both photovoltaic powered pump costing and diesel generator powered pump costing

Table III: PVPs Pump Costing (initial cost)

PV System Cost	Price (₦)
PV Array	500,000
PV structure	200,000
Pipe, Cable, Rope	300,000
Accessories (casing, gum)	250,000
Installation	200,000
Transportation	100,000
Grundfus Pump SQFlex (120-200m)	1500000
Drilling	500,000
Total	**3,550,000**

Table IV: DPs Pump Costing (initial cost)

DP System Cost	Price (₦)
Diesel engine	400,000
Structure (wooden, zinc and flooring only)	100,000
Pipe, Cable, Rope	300,000
Accessories (casing, gum)	250,000
Installation	250,000
Transportation	100,000
7hp Pedrollo hydraulic submersible pump	300,000
Drilling	500,000
Total	**2,200,000**

V. RESULTS AND DISCUSSION

Note that in both tables (table III and table IV), the price of tank and base is not included. This is simply because the two pumps has the same volume of tank to be filled and whether added or not, it does not really have much impact in the analysis.

Table V. Manufactures diesel engine consumption rate (NAMREP, 2006)

kW	L/h
1.9	0.5
3.0	0.7
4.0	1.0
5.0	1.3
5.8	1.4
6.7	1.5
8.6	2.0
11.0	2.4
13.1	2.9
16.8	3.6

From the tables (III and IV), $Cic_{\mathbf{PVP}}$ = **₦3,550,000** and $Cic_{\mathbf{DP}}$ = **₦2,200,000.**

Cr here is zero for both option as the year of comparison is 5 years.

The energy cost, Ce, which is the future cost, is the total sum of diesel cost and transportation cost for the whole year in question. For a 5.8KW will consume 1.4ltrs for one hour(table 5). Since in a day, the generator works only 5hours, so in a year it will be, 365 days x 5 for one year. This will be 1825 hours in a year for five (5) years, it will 9125 hours for five years. The total energy consumed will be 1.4ltrs x 9125 , this will amount to 12775ltrs. A litre of diesel cost **₦230** i.e **₦230/ltr.** So that for 12775ltrs will be **₦2,938,250** taking 10% of diesel cost for transportation will be **₦293,825.** Therefore total energy cost will be **₦3,232,075**

The maintenance cost, Cm can also be obtained as follows table 2;

Minor Services = 8 times per year and in 5 years = 40 times. Cost per service is assumed to be **₦5000/service** = **₦200,000** for five years

Major services = 2 times per year and in 5 years = 10 times. Cost per service assumed to be **₦10,000/service** and 5 years = **₦1,000000.**

Overhaul = 2twice in 5 years, assuming **₦100,000/service = ₦200,000**

Total cost for the whole maintenance will be **₦200,000 + ₦1,000,000 + ₦200,000 = ₦1,400,000**

Table VI: Typical diesel generator maintenance and fuel costs

Maintenance and fuel	Total cost (₦)
Minor service	200,000
Major service	1,000000
Overhaul	200,000
Cost of diesel	3,232,075

For solar, the total maintenance cost is assumed to be 10% of the initial cost for the period under research = **₦355000.**

And the cost of removing carbon dioxide from the atmosphere ($Cenv$) is assumed to be 20% of the energy cost i.e 20% of Ce = **₦646,415**

$Life\ Cycle\ Cost$ (DP) =Cic+Ce+Cm+$Cenv$+(zero in this case)

= **₦3,550,000** + **₦3,232,075** + **₦1,400,000** + **₦646,415** = **₦8,828,490** and that of solar is as below

$Life\ Cycle\ Cost$ (PVP) =Cic + (zero) + Cm + $Cenv$ (zero) + (zero)

= ₦3,550,000 + ₦355000 = ₦3905000

All comparisons are based on the assumption that the pumping systems are fully utilised, i.e. the solar pump is used every day of the year (5years) and the diesel pump is used according to the selected pumping schedule, to meet the average daily delivery of the solar pump. The study presents some results as a function of the hydraulic load. This is illustrated in Table (3, 4, 5 and 6). Since the LCC varies with daily flowrate and head, two daily flowrate have been considered in this work, which is the DP and the PVP. It can be seen that the LCC of the PVP was initialy very high as compared to that of DP. The study later showed that the overall cost of the solar powered borehole system was lower than diesel powered and the saving when the two are compared using LCC was **₦4,923,430** with a factor of 2.3 The high operational costs of diesel systems prevented it from being cost-effective. Comparing the power supply costs of both systems over a 5-year life cycle showed that the diesel-generator powered system has a present value cost of about 230% higher than that of the solar powered unit. The outcome of this study showed that the PV pumping systems include low operating cost, unattended operation, low maintenance costs, easy installation, and longer operating life.

In a comparison of fueled pumps versus PV in 2014, Nwobi study showed that PV powered pumps to have the lowest life-cycle costs for PV array sizes of 0.75kWp, in his report, itv was concluded that, comparing the power supply costs of both systems over a 20-year life cycle showed that the generator powered system has a present value cost of over two hundred times (≥200 %) that of the solar powered unit.

A study by GTZ (Posorski, Haars, 1995) in seven countries concluded that PV pumping systems for drinking water are economically competitive in the range of small diesel pumps (1.4 kWp solar systems).

It is clear evidence that the solar power pumps are better used in the rural areas to provide suitable water supply than the diesel powered hydraulic pumps. The solar powered bore hole has more simplified wiring diagrams unlike the petrol, diesel or utility company wiring/circuit diagrams. This simplified circuit diagram and wiring diagram is shown in figure 2 (Circuit diagram) and Figure 3 (Pictorial Electrical wiring diagram).

The comprehensive circuit diagram of the solar powered borehole is depicted in figure 2. This circuit explains the sequence of operation and it is sectioned into three, which is the PV section, Control section and the Pump section. Failure in any of the section means failure to all.

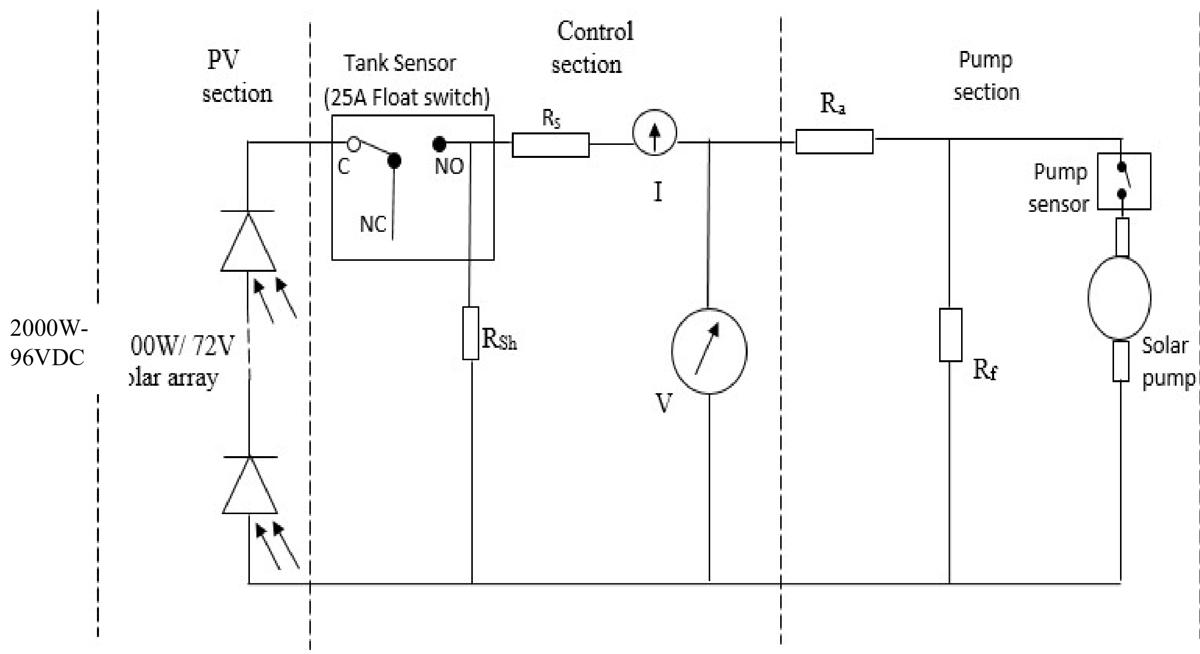

Figure 2: Solar Powered Borehole Circuit Diagram.

The power supply system adopted was a system with a direct connection from the solar arrays to the pump. No inverters or battery banks were incorporated in the design. This is to keep the system as simple and basic as possible and to eliminate costs and the technical expertise associated with the installation and maintenance of a battery-backup system. Since the installation is basically solar powered, it is best to make it able to run for a long time with little or no intervention by way of maintenance or repairs. The use of a direct-connect system which has a direct current output also means a direct current (pump) was used in the design. With the power requirement for the water pump known, the number of solar panels making up the solar array was determined.

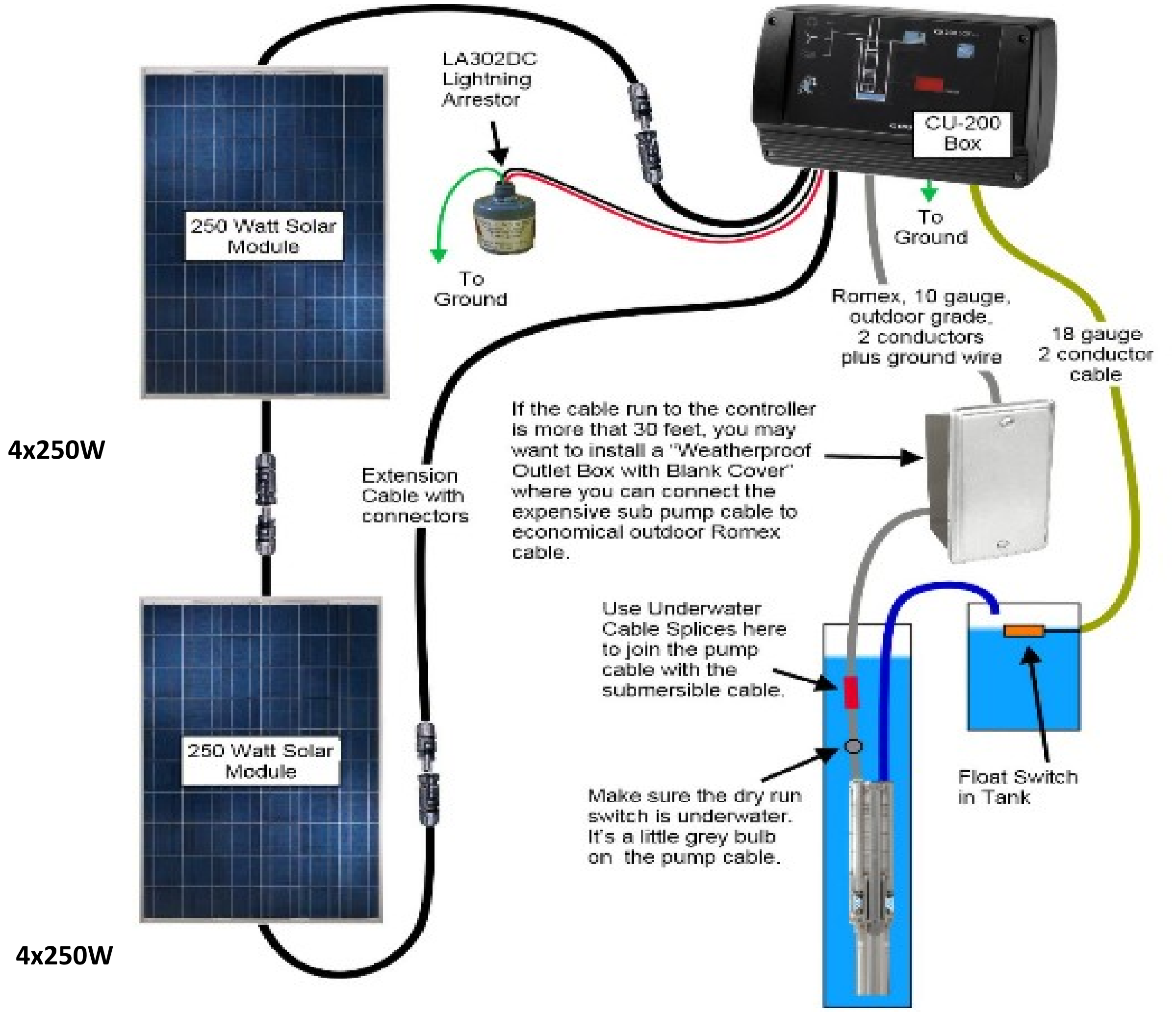

Figure 3: Pictorial Electrical Wiring Diagram for 2000 W/96 V Solar Powered Pump System

LCC	**[₦]**
Solar Pump	**3,905,000**
Diesel Pump	**8,828,490**
Savings	**₦4,923,430**
Factor:	DP/PVP 2.3

The study found that the overall cost of the solar powered borehole system was lower than diesel powered and the saving when the two are compared using LCC was **₦4923430** with a factor of 2.3 The high operational costs of diesel systems prevented this to be cost-effective.

VI. CONCLUSION AND RECOMMENDATION

Conclusion

In actual fact, solar powered borehole systems are expensive technology especially on the initial cost of acquiring and installing the equipment. Looking at the cost of running both for a period of five years. This study found that under the actual conditions and assuming that the various assumptions are correct, solar energy water pumping systems are the most cost-effective for rural areas in Nigeria.

In this study, the following conclusions can be made:

This design provides a model that can be applied to any stand-alone solar-powered water supply system, especially in the rural areas of Nigeria.

The environmental benefits of using solar energy for this project can also be visualized by considering the potential Carbon dioxide emission removed from the atmosphere.

With the cost implications of the diesel generator-powered system which mainly come from maintenance and fuelling, solar powered borehole low sustainability as compared to the diesel generator-powered system since solar powered borehole requires little periodic maintenance.

Recommendation

This study recommends the promotion of solar powered borehole technologies that uses renewable energy sources. The government should be highly involved to support these

initiatives in terms of technologies and finance once they are handed over to the local communities. Through this research study, more studies should be done to comprehend:

i. The extent of using these technologies into reduction of mortality rate with respect to water born diseases, health hazards generated from burning of fuel wood and treatment costs;
ii. The extent of carbon reduction into the atmosphere through carbon emission reductions (CERs) calculations through the substitution of solar energy into purification of portable water.

REFERENCES

[1]. Deen, M., Mukib, M. and Shakir-ul, H., K. (2014). Assessment and Evaluation of Solar Irrigation System in Bangladesh Electrical and Electronic Engineering Islamic University of Technology Dhaka, Bangladesh.
[2]. United Nations Children's Fund (UNICEF) (2016). Scaling up solar powered water supply systems: a review of experiences.
[3]. Solar Electric Light Fund (SELF) (2008). A Cost and Reliability Comparison Between Solar and Diesel Powered Pumps
[4]. Mico weather, (2017). Daily weather forecast powered by Amber weather forecast.
[5]. Nwobi, E. U. Ajide, O. O. and Abu, R. (2014). Design and Cost Analysis of a 0.75 Kw Solar Powered Water Pumping System
[6]. Ministry Of Mines and Energy Barrier Removal To Namibian Renewable Energy Programme (NAMREP) Final Report: (2006). Feasibility Assessment for the Replacement of Diesel Pumps with Solar Pumps
[7]. SELF, (2008). Cost Reliability Comparison between Solar Powered and Diesel Powered Pumps
[8]. World Health Organization (WHO), (2011). Guidelines for Drinking-Water Quality: 4th Edition Average consumption per person i. e domestic and individual use only
[9]. www.groundfos.com