

DESIGN AND COST ANALYSIS OF A 0.75 kW SOLAR POWERED WATER PUMPING SYSTEM

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ABSTRACT

Solar powered systems have been built for various applications ranging from public lighting to water supply units. Robust efforts have not been made in the systematic study of the effectiveness and viability of such systems as it applies to the Nigerian techno-economic situation. The objective of this study is to design a solar photovoltaic (PV) powered water supply system for rural areas in Nigeria using Onipe, a village in Ibadan without electric grid connection as a case study. The methodology adopted for this study involves field survey and detail system design and analysis. The design of the solar powered system was based on the estimated daily water supply rate of 15,000 litres with a view to obtaining a cost-effective and energy-efficient system to drive it. A review of pump technologies, alternative energy applications in some parts of the world and an assessment of the potentials of various alternative energy technologies in Nigeria and particularly in the study location was undertaken. The data gathered from the location which include the required water supply capacity and the likely depth of the borehole were applied in the design. This depth was estimated by a geo-physical survey using Vertical Electric Sounding (VES) techniques. Pipe sizing, pump sizing, power supply design and protective devices selection were all carried out during the design of the system. Finally, a cost-comparison analysis between the solar-powered system and generator powered system was done using Life-Cycle costing and analysis. Results obtained from the study showed that a 0.75 kW solar powered unit can supply the desired water quantity. 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 times ($\geq 200\%$) that of the solar powered unit. In addition, the annual Carbon dioxide emission tonnage from the generator powered system is estimated to be about 3.2 tonnes whereas the solar powered system is emission free. The outcome of this study will find useful modularization applications in villages with similar characteristics and can also be easily adjusted to fit larger or smaller sized communities.

Keywords: Solar PV, Design, Pumping System, Modularizations and Cost Analysis

1. INTRODUCTION

There is growing concern among researchers on the exploitation and application of renewable energy for provision of basic needs in the villages and rural communities where there is very little or no access to national grid supply. This concern is necessitated from the fact that the present use of fuel generator is not only expensive but the associated intense emissions of carbon oxide gases constitute environmental threat. Several studies have demonstrated how renewable energy can be provided at a more economical level in a way that it can be easily affordable and practically implementable in the poor rural communities. The Sun, wind, hydro, biomass and geothermal have been identified as the prominent renewable energy sources capable of meeting energy needs of rural dwellers (Ijeoma, 2012). Extensive studies revealed that solar energy is greatly employed in the world rural communities to provide electricity for lighting and in the most recent time, as energy source for heating systems and provision of basic amenities such as water pumping systems.

Numerous research efforts have been made in the application of solar photovoltaic (PV) for water pumping systems. Different programmes are now available for training personnel in acquiring skills necessary for installation of solar PV for water pumping systems. Barbosa et al. (2000) studied a partnership experience between a University and hydroelectric power plant on solar PV water pumping systems installation training programme. They further corroborates the growing acceptance of solar PV for water pumping systems. Solar powered water pumping has the potential to bring sustainable supplies of potable water (Short and Thompson, 2003). Equally, Khattab et al. (2011) paper focused on the implementation of solar technologies on the development of rural communities. Their paper satisfactorily described how solar technologies can be utilized to provide basic needs such as clean water. The use of photovoltaic has been considered as one of the most promising applications for water pumping system. Ghoneim (2006) carried out a design optimization of photovoltaic powered water pumping systems. The author developed a computer simulation program which helped in determining the performance of the solar PV system in the Kuwait climate. The author's study showed that a newly developed motor-pump model can be used reliably in designing and calculating the long term performance of a PV water pumping system. Wong and Sumathy (1999) reported that some efforts have been made by research scientists in exploring solar PV for irrigation water pumping for farm activities. Hamidat et al. (2003) work focused on small-scale irrigation with photovoltaic water pumping system. They were able to develop a suitable PV system for irrigation of two selected stations in Sahara regions of Algeria. The findings showed that for low heads, the possibility of using photovoltaic water pumping system

for small scale irrigation of crops in Algerian Sahara regions was enormous. Glasnovic and Margeta (2007) have also developed a model for sizing of photovoltaic irrigation water pumping systems. From the previous works, there is no doubt that the application of solar PV has made a great impact in Agricultural practices through irrigation system especially during the dry season when there is low volume of rainfall or total drought .

The provisions of potable water supply remain a recurring challenge in rural communities. The importance of clean and hygienic water supply cannot be over emphasized in the efforts of any country to improve the health status of her citizens and reduce all water borne diseases to the barest minimum. Solar PV has been found to be a useful energy resource for providing functioning pumping water system in rural communities. A study which focuses on the application of Photovoltaic in the design of pumping system for drinking water has been carried out (Ammar et al. 2007). Hrayshat (2004) work has also shown the application of solar energy technology for water pumping system. In the study, ten sites in Jordan were selected based on the available data. Results obtained from the study showed that there is interesting potential for solar water pumping system in some stations in Jordan. In the same vein, the work of Al-Ibrahim et al. (1998) is on the design procedure for selecting an optimum photovoltaic pumping system in a solar domestic hot water system. A pilot study on the application of solar energy for domestic drinking water in India government houses was carried out by Akshat (2013). In the work, a DC pump was selected as way of reducing the initial cost of solar pumping system. This is because DC pumps uses one third to one half of the energy of a conventional AC pump. Findings from the study showed that a DC centrifugal pump could be selected to give a maximum flow rate of 8 litres per minute at approximately 14.5 watts of power. The system performance is considered satisfactory when kept on ground level where it will pump the water to a water storage tank at an approximate height of 15 feet from the ground. This paper is indeed a good contribution to the literature and has provides illumination on how to explore solar energy for pumping water at minimal cost. The study of Abdeen (2001), Maurya et al. (2013), Ahmad et. al (2014) and many other works have shown the enormous applications of solar PV in the provision of drinking water for rural dwellers.

Extensive literature review shows that robust efforts have not been made in Nigeria in the exploitation of solar PV for water pumping system to a satisfactory level. However, the effort of some researchers in the study that bothers on application of solar PV for provision of drinking water in rural areas of Nigeria is commendable. For instance, Yahya and Sambo (1995) carried out a study on design and installation of solar PV powered water pumping system at Usmanu Danfodiyo University, Sokoto, Nigeria. They successfully presented the outcome of powering a conventional A.C. type water pump by photovoltaic solar modules. The installed solar PV system

was tested and its results showed a satisfactory performance of the system. In the contribution of Bolaji and Adu (2007), a design analysis was done on the practicability of adapting solar PV system for rural applications in Nigeria. Although there are some other research efforts on how solar PV pumping system could be used successfully in Nigeria, the efforts are however insignificant when compared to numerous water supply problems encountered in Nigeria rural communities. In addition, Nigeria is far behind in the area of provision of potable water for her citizens by means of Solar PV pumping system.

Therefore, this study is aimed to contribute to a study that focuses on the effective and efficient use of Solar PV pumping system 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 Onipe, a village in Ibadan without electric grid connection as a case study.

2. METHODOLOGY

In the Design of a Solar PV powered water supply system, the following preliminary works were undertaken:

- Determination of the water requirements
- Establishment of water availability
- Determination of characteristics of the water source (depth, quality, drawdown)
- Amount of solar insolation available for given location

The above listed parameters were used to determine the capacity of pump required and consequently the amount of energy needed to power the system. The solar insolation value was obtained from readily available data from previous studies.

2.1 Description of Study Location

Onipe is a village in Oluyole local government area of Oyo state in Nigeria occupying a land mass of about 4,500 square metres (excluding farmlands). It is situated along Ijebu-Ode road on the way out of Ibadan. The community is mostly an agrarian one with a population of about 1,200 inhabitants split into about 250 households. The villagers engage in farming both for subsistence and commercial purposes and depend on the rainy season for irrigation of their farmlands. A survey of about 30 households in the community revealed the average daily water consumption per household to be about 200 litres. Being within 15 kilometers radius from Ibadan city center, the average daily insolation values for Ibadan was used for this design. Table 1 shows the average insolation values on a monthly basis over a one-year period.

Table 1: Monthly Insolation values for Ibadan (Measured in kWh/m²/day onto a horizontal surface)

JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
5.45	5.64	5.57	5.27	5.00	4.49	3.93	3.73	4.05	4.65	5.06	5.30

Source : Solar Electricity Handbook
 (<http://www.solarelectricityhandbook.com/solarirradiance.html>)

From the Table 1, the annual average value for the location is 4.85 kWh/m²/day and this was used in the design of the solar power supply system. The availability of water bodies close by and the existence of other functional borehole systems in the area was a reasonable pointer to the viability of the aquifer. For the design, however, a geo-physical survey using the Vertical Electrical Sounding (VES) system was done to obtain an estimate of the borehole depth. This information is important for an optimal design of the power supply system as well as selection of the borehole pump.

2.2 Initial Design Considerations

A survey of 30 households in Onipe community indicated that the average household used about 200 litres of water per day for drinking, cooking, washing and other domestic purposes. This value amounts to a daily consumption of about 50000 litres per day for 250 households. To locate a productive site for the development of a borehole, a geophysical/hydro geological survey using Horizontal Electrical Profile Line and Vertical Electrical Sounding (VES) was conducted within the study area. From the survey carried out, the estimated depth of the borehole was put at between 45 and 50 metres. The actual yield of the borehole could not be ascertained (because this can only be confirmed from a well test done after drilling). An assumption here is that the borehole will be able to yield at least 3.0 m³/h . This would fulfill the water needs of the system as designed. A two-day storage capacity to hold the water needs of the system as designed was also considered. The reason for this is to have a buffer in the event of cloudy days, rainy days and days of poor insolation. Again, the target water supply volume was estimated at 20% of the total water consumption which would be specifically potable water for drinking and cooking. According to the United Nations Water Federated Water Monitoring System, the average drinking water needs of an individual ranges between 2-4 litres daily. Hence using the upper limit value for Onipe which has a population of about 1,200, the estimated drinking water needs would be 4,800 litres per day. This amounts to

about 10% of the total daily water consumption. An additional 10% in the design is expected to take care of some of the cooking water needs of the community.

2.3 Estimation of Water Supply Rate

The hourly water output of the system which is essential to pump sizing 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 insolation values for Ibadan (see Table 1). The formula applied is:

$$\text{Required Hourly Rate} = \frac{\text{System water supply capacity}}{\text{Average daily Insolation}} \quad (1)$$

$$\text{Water usage per household} = 200 \text{ litres per day}$$

$$\text{Number of households} = 250$$

$$\text{Total volume of water requirements per day} = 250 \times 200$$

$$= 50,000 \text{ litres per day}$$

Design capacity is 20% of total water consumption:

$$0.2 \times 50,000 = 10,000 \text{ litres per day}$$

For a 2 day storage capacity, we opt to have a daily water supply rate of 75% total holding capacity to allow for 25% redundancy in storage capacity:

$$10,000 \times 2 \times 0.75 = 15,000 \text{ litres per day}$$

Hence the borehole system will be designed to produce a minimum of 15,000 litres of water daily.

The average sun hours per day in Ibadan is 4.85 hours (see Table 1)

Hence:

$$\frac{15,000}{4.85} = 3092.78 \text{ litres per hour}$$

$$\cong 3.10 \text{ m}^3 \text{ per hour}$$

Hence a borehole yield of at least $3.10 \text{ m}^3/h$

2.4 Sizing of Solar Power Supply System

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 location of the water supply system is in a rural area, 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 can be determined. Many PV panel manufacturers recommend an increase of the minimum peak power value by 25% to account for any potential reduction in power due to high heat, dust, age and cloud cover or reduced insolation.

Thus:

$$\text{Installed Solar Panel Power} = \text{Required Power} \times 1.25 \quad (2)$$

While selecting the solar panels, 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 12, 24 and 48 volts are connected in series to obtain this higher voltage and a reduced current. The total system voltage and power are given by equations 3 and 4;

$$\text{Total System Voltage} = V_1 + V_2 + V_3 + \dots + V_n \quad (3)$$

$$\text{Total System Power} = P_1 + P_2 + P_3 + \dots + P_n \quad (4)$$

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;

$$\text{Maximum Current of the array} = \frac{\text{Total Power of the array}}{\text{Total Voltage of the array}} \quad (5)$$

The power, voltage and current characteristics of the solar array were matched with the operating parameters of the pump.

A direct current pump was used with a power rating of approximately 600 Watts. Each solar panel could range between 12 Volts and 48 Volts. To provide a power supply of 600 Watts and 96 Volts, four 24 Volts panel or six 16 Volts panels are used.

Applying equation 2 to include the 25% incremental design allowance for optimal power generation;

$$\text{Installed Solar Panel Power} = 600 \times 1.25$$

$$\text{Installed Solar Panel Power} = 750 \text{ Watts}$$

A solar array with a power capacity of 750 Watts was used for the system. For an array of four 24

$$\text{Volts panels, the power for each panel is: } \frac{750}{4} = 187.5 \text{ Watts}$$

For an array of six 16 Volts panels, the power for each panel is:

$$\frac{750}{6} = 125 \text{ Watts}$$

2.5 Sizing of Petrol Generator Power Supply System

Using a petrol generator for this system, it is rational to reduce the operational hours per day as well as the storage capacity in order to prolong the life of the generator and to have a practical system. For this design, the storage capacity is 10,000 litres, which is the daily 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 two 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 5 to 8 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.

Assuming a 2-hour daily operational period, the new hourly rate is calculated thus:

$$\text{Hourly rate} = \frac{10000}{2} = 5000 \text{ litres/hour}$$

The new hourly rate is thus 5 m³/ hour; using this value to estimate the hydraulic power:

$$P_{hyd} = \frac{\rho \times g \times Q \times H}{3600 \times 1000} \tag{6}$$

$$P_{hyd} = \frac{1000 \times 9.82 \times 5 \times 58}{3600 \times 1000}$$

$$P_{hyd} = 0.791 \text{ kW}$$

The hydraulic power required to pump 10000 litres of water in 2 hours is approximately 0.8 kW.

Assuming mechanical losses of 15%,

the required power for the motor-pump unit is = $1.15 \times 0.8 = 0.92 \text{ kW}$

Thus a pump rated at 0.92 kW (about 1.2 hp) is required for the system. For ease of procurement, a 1.5 hp pump is used for this system. The generator for this system is rated at 2 times the nominal power of the pump. Hence:

Generator power = 2×1.12 (1.12 kW = 1.5 hp) = 2.24 kW

A 2.3 kW generator is used to supply the energy required by this system.

2.6 Life Cycle Cost Comparison for the Solar and Generator Powered System

The analysis was carried out using Life Cycle Costing (LCC) as this method captures every part of the useful duration of the system from procurement to disposal. When used as a comparison tool between possible design alternatives, the LCC process shows the most cost-effective solution within the limits of the available data. The cost elements considered, however, are those that are directly related to the provision of energy to the water supply system. Other cost elements such as wiring, storage and support systems are considered fixed for the two systems and thus add little or no value to a comparative analysis. Equation 7 shows the life cycle costing of a pump used in an industrial process. For the purpose of this study, certain cost elements would be removed since they may not apply directly to the problem at hand.

$$\text{Life Cycle Cost} = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d \quad (7)$$

Where:

C_{ic} = Initial costs, purchase price (pump, system, pipe, auxiliary services)

C_{in} = Installation and commissioning cost (including training)

C_e = Energy costs (predicted cost for system operation)

C_o = Operation costs (labour cost of normal system supervision)

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

C_s = Down time costs (loss of production)

C_{env} = Environmental costs (contamination from pumped liquid and auxiliary equipment)

C_d = Decommissioning/disposal costs (including restoration of the local environment)

The cost elements applicable directly to making a comparative analysis between a generator-powered unit and solar powered unit pumping unit and a solar powered pumping unit are:

- i. The initial costs
- ii. Energy costs
- iii. Maintenance and repair costs
- iv. Environmental costs
- v. Replacement costs (Not included above)*

(The Life cycle period is 20 years and pump replacement will occur within that period)

The equation for the Life Cycle Cost Analysis of these two systems is thus:

$$\text{Life Cycle Cost} = C_{ic} + C_e + C_m + C_{env} + C_r \quad (8)$$

Where:

C_r = Replacement Costs.

The actual future cash flow of costs occurring annually and at specified times in the future during the system's life cycle were projected using the future value as illustrated in equation (9):

$$F = PV(1 + i)^n \quad (9)$$

Where:

F= Future worth; PV= Present value (worth); i= Interest Rate (Inflation rate); n= Number of Years.

To achieve a common basis for comparison, the present worth of the sum of all future values was calculated using equation (10):

$$PV = \frac{F}{(1 + i)^n} \quad (10)$$

Where: F=Future value; PV=Present value; i=discount rate (rate of inflation); n=number of years

This present worth and the initial cost are presented as the total system cost.

3. RESULTS SUMMARY AND DISCUSSION

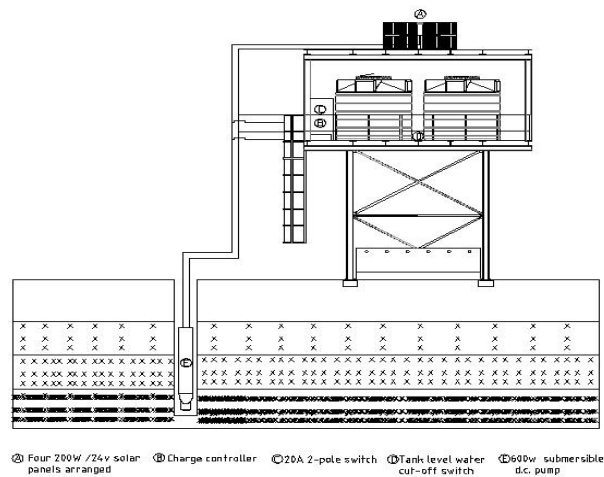


Fig 1: Electrical Wiring Diagram for 800 W/96 V Solar Power Supply System

Fig. 1 shows a one-line electrical diagram of the 800 Watts, 96 volts solar power unit used for the water supply system. In this option, four 200W/24V solar panels are connected in series (800 Watts is used for practical reasons- 200 Watts panels are more readily available commercially). The water cut-off switch is automatically set to disconnect power from the pump when the water in the tank gets to a preset level. The charge controller or solar pump controller includes a low water level cut-off switch to protect the pump from damage in the event of drop in the borehole’s water level below the suction of the pump.

Based on the calculated water storage capacity of 15,000 litres (3750 gallons), four 1000-gallon plastic tanks were selected for the water storage system. Fig. 2 shows arrangement of the storage and support system. The height at which the tanks are stored is 4 metres.

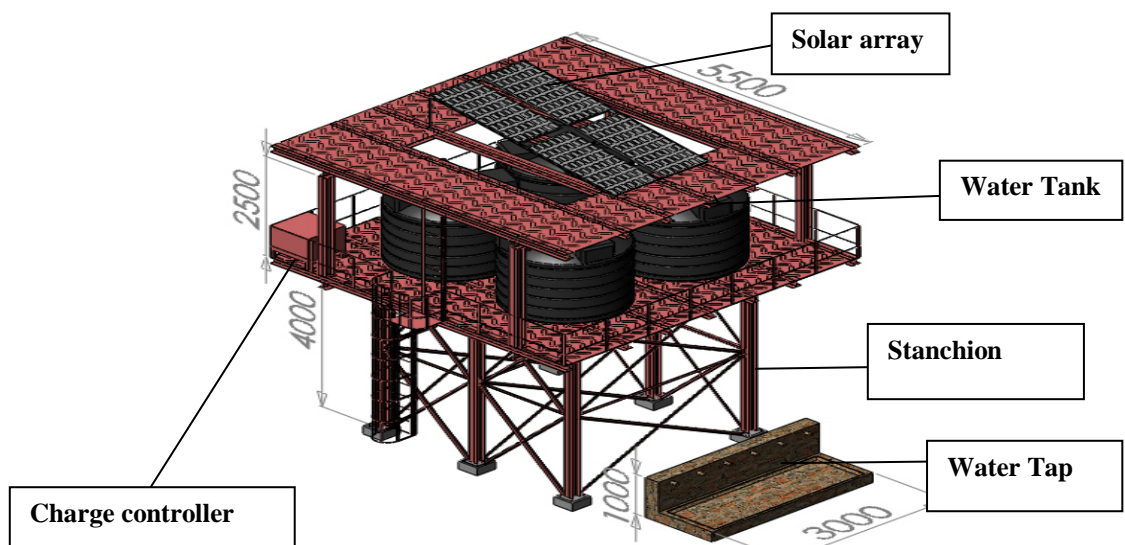


Fig. 2: Solar Photovoltaic Water Pumping System

Table 2: Recommended Maintenance Schedule for Solar Powered Water Supply Unit

Component	Maintenance Routine	Frequency
Solar Panels	Use water to carry out a light shower wash of the panel's surface	Quarterly
Solar Controller	Check the controller box for any signs of wear to the protective cover	Every six months
Wiring	Inspect cable insulation for wear and tear	Every six months
Piping	Check for leaks (Leaks upstream of the tank can Reduce system efficiency considerably)	Weekly

Table 2 is a maintenance routine suggested for this system. From the Table 2, it can be seen that there is minimal maintenance required over the life of the equipment. Unlike what is obtainable in a generator powered system, where the generator has to be maintained through a more labour and cost intensive approach (Regular changing of lubricating oil and worn parts), this system requires little or no expertise to maintain. The cost analysis showed that the life-cycle cost of the petrol generator-powered system is 200% that of the Solar-powered system excluding cost of storage, wiring and support structures, which are invariably the same for both systems. The Life-Cycle cost analysis looks at the costs that would vary over time based on the power supply system adopted. The other cost component of the system (about ₦ 1,972,120), is fixed and as such has only an initial cost component.

4. CONCLUSIONS

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. The generator-powered system is expected to pour out an estimated Carbon dioxide emission of about 3,204 Kilograms per annum to the environment while the solar-powered system is carbon free.
- With the cost implications of the generator-powered system which mainly come from maintenance and fuelling, its sustainability is low compared to the solar-powered system which requires little periodic maintenance. Though the solar-powered system has a higher initial cost of over 250% when compared to that of the generator-powered system, its

overall functionality and life-cycle benefits overshadow that initial cost and makes it down as a more cost-efficient and technically viable alternative to the generator-powered system.

- The system designed in this study uses a 750 Watts solar array to supply 15,000 litres of clean water per day in an area without electricity grid connection.

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