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An Appraisal of Solar PV Systems over Diesel Generators for Off-Grid Water Projects in Rural Africa for Sustainable Development

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Abstract: *This paper presents an appraisal of solar PV systems over diesel generators for off-grid water projects (a Tertiary Education Trust Fund Sponsored Project 2017/2018, The Federal Polytechnic Bida, Niger State). The study was done to investigate the potentiality and cost effectiveness of using solar borehole system in Lavun local government area of Niger State. The Analysis of the solar powered system was based on the estimated daily water supply rate of 28,000 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 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 340% 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.*

Keywords: *Solar PV, Diesel Generator, solar borehole*

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I. Introduction

Population growth and climate change have put a lot of pressure on water resources the world over. Water is in high demand to meet the varied needs of the ever-growing population. It is estimated that 884 million people lacked access to potable water supply and that 84% of them lived in rural areas (WHO/UNICEF, 2010). Two billion people worldwide depend on groundwater for drinking and its regional significance is evidenced by its provision of 70% of potable water in the European Union, 80% of rural water supply in sub-Saharan Africa, and 60% of agricultural irrigation water in India (IAH, 2006), (Abunkudungu, 2014).

Many sparsely populated rural regions in Africa, have difficulties with accessibility to reliable supply of fresh water. This is further exacerbated by the poor economical states of these areas. Groundwater offers the most suitable source of water in these areas, due to non-existent modern water systems and lack of widespread surface water sources as well as the generally cleaner nature of groundwater. This study was conducted in order to determine whether solar-powered borehole pumps could provide an attractive alternative to the currently used diesel powered borehole pumps, with comparisons made across functionality, life time cost and maintenance requirements.

II. Literature Review

Solar Electric Light Fund (SELF) (2008) compared a solar array of 1900 watts against a 4 kW diesel generator. Both power an equivalent pump of approximately 1 horsepower. Several simulations were performed to gauge the effect of the price of fuel and the fuel efficiency of the diesel generators. The study concluded that solar pumping systems are inherently more reliable than diesel powered systems .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, it 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 times (≥200 %)that of the solar powered unit. However, Nwobi (2014) only compared using the life cycle cost. In another development, a comparative analysis was done but in this,

a Solar Powered DC refrigerator and a conventional AC powered refrigerator by Raheem (2018). The comparison was based on current consumption and corresponding cooling effect of each refrigerator, it was concluded that, with the same volume of item in both refrigerators and refrigerator capacity, the DC unit shows more efficiency since it has a smaller compressor made by DANFOSS, and even with low voltage the unit was able to operate with a reasonable cooling effect. Its reliability in terms of power supply supersedes the AC unit.

III. Methodology

The methodology adopted in determining the viability of solar PV systems over diesel power generators for borehole water pumping, apart from research into previous studies on the matter, involved comparing the cost, reliability, maintenance requirements and performances of each of the pumps by observing the aforementioned parameters on an existing diesel-powered borehole system and retrofitting same borehole (with same storage capacity) with a solar powered pump.

3.1 Description of Study Location

The study area is located Lavun local government; an area that is at an elevation of about 164 meters above sea level with a population density of 50 persons per square kilometers. It is close to boundary between Bida and Doko. Bida is the administrative head quarter of Bida local Government area town. Dokois an area that is best describes as rural area.The villagers engage in farming for subsistence as well as commercial farming and sometimes depend on water from a stream for washing, drinking, bathing, and cooking; when the diesel-powered borehole system fails. The area lies within 5 kilometers radius of Bida, hence average daily insolation values for Bida were considered for this study.

Table 1. Monthly Insolation values of Bida (Measured in kWh/m^2/day onto horizontal surface, July 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	JAN	FEB	MAR	APR	MAY	JUN
6.7	3.2	6.3	8.9	6.7	4.1	7.2	5.5	8.3	7.1	6.5	6.2	4.5	3.9	5.5	7.0	7.9	6.8

FromTable 1, the average solar irradiance for this periodof 18 months was estimated to be 6.4kWh/m^2/day and this was considered in the design of the solar powered supply system.

Table 2. Average Monthly sunlight hours forBida. Source: Mico weather, 2017 Daily weather forecast powered by Amber weather forecast www.minna.climatemps.com/sunlight.php

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Average Sunlight Hours/Day	08:23	08:33	08:17	07:38	07:42	07:04	04:38	03:38	05:32	08:15	09:10	)9:00	07:18
Average Daily light Hours & Minutes/Day	11:37	11:48	12:03	12:19	12:33	12:40	12:37	12:25	12:09	11:53	11:40	11:33	12:00
Sunny & Cloudy) Daylight Hours (%)	73 (27)	73 (27)	69 (31)	62 (38)	62 (38)	56 (44)	37 (63)	30 (70)	46 (54)	70 (30)	79 (21)	79 (21)	79 (39)
Sun Altitude at Solar Noon on the 21st Day	**60.4**	**69.6**	**80.5**	**87.7**	**79.4**	**76.2**	**79.1**	**87.4**	**80.9**	**69.3**	**60.2**	**57**	**74**

3.2 Estimation of Water Supply Rate and Determination of Pump Size

The installed water storage capacity is 28,000 litres at a head of 40 meters. The daily sun hours is a value derived from the average daily solar irradiance in Bida. The formula reported by Nwobi (2014) was used and is given as;

$$DF = \frac{SWSC}{ADI} \qquad (1)$$

Where DF is the daily flowrate (m^3/day), SWSC is the system water supply capacity (kWhm); in this case SWSC is the storage capacity of the tank which is 28,000 litresand ADI is the average daily insolation (kWh/m^2/day)

Recall from table 1; the average sun hours per day in Bida was given as 6.36Kwh/m^2/hour

Therefore, the daily flow rate was calculated to be 4.40m^3/hour. From table 2, the average yearly sunlight hours per day and the average yearly daylight hours per is 7.18 hours and 12 hours respectively. It is also observed (from table 2) that the minimal day light hours of 11.33 hours is expressed throughout the year in December. And solar panels use the energy from daylight, as opposed to sunlight to produce electricity, so panels do not need direct sunlight to work (www.theecoexperts.co.uk/solar-panels/). In essence, even in slightly cloudy conditions light will diffuse through the clouds and reach the solar panels.

This implies that the solar pump needed must be able deliver at least2.47m^3 of water per hour. Hence the choice of 4SSC3.6/138-72/1000W; figure 1 (www.jilupumps.com) which can deliver 2.7m^3 per hour at a head of 40 meters.

3.3 Sizing

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

3.3.1 Photovoltaic (PV) Pump

Throughout, the study the delivery of the PV pump system is based on the dailydelivery 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/m^2/day has been used. This values falls within the allowable range provided by the manufacturer (i.e between 5 and 7kWh/m^2/day), which is a representative average of Bida solar irradiance. Therefore 1,000Wpeak solar pump (figure 1) was used as it is provided in the manufacture's charts with a dc input of 40-100VDC at operating current of 8A. The formula reported by Nwobi (2014) was used and is given as;

$ISPP = RP \times 1.25$ (3).

where ISPP is the $InstalledSolarPanelPower$ (watts), and RP is the $RequiredPower$(watts).

It should be noted that the pump size is 1000W (figure 1) which means required power is 1000W.

Therefore, Installed Solar Power = 1250W. It was observed that this combination will yield odd arrangement, so 1,500W was chosen instead, which is even (3 pieces of 250W for each string of two stringed parallel connections). While selecting the solar panels (figure 2), a higher voltage system was preferred in order to compensate 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

$TSV = V_1 + V_2 + V_3 + . \ldots . + V_n$ (4).

where,TSV is the total system voltage(V), $V_1 = V_2 = V_3$ = maximum voltage rating of each panel and n = number of panel voltage

$TSP = P_1 + P_2 + P_3 + \ldots + P_n$ (5).

Where; TSP is the t$otalsystem$ power (watts)

n = number of solar panels in the array,

V= $P_1 = P_2 = P_3$= Rated power output of each panel. Also the maximum current of the array was calculated thus;

$$\mathrm{MCA} = \frac{\mathrm{TPA}}{\mathrm{TVA}} \; 6.$$

where MCA is the maximum current of the array (A),TPA is the total power of the array (P) and TVA is the total voltage of the array. So from equation 4 and 5, n = total number of panels in array, here three panels were chosen for one array. Therefore n = 3, each of 250W/24V.

Total system voltage = 72V

Total system power = 750W

In this design, two strings of the 750W were used. This means that, the two strings (2 separate arrays) of the solar panels were connected in parallel; the total power will be (750 W + 750W) which amount to 1500W. Invariably the total power, P_T = 1500W which is in conformity with calculated Installed Solar Power for the Pump (pump selected is rated 1000W, which means that solar panels (figure 2) used is sufficient to power the pump.

The maximum current of the array was calculated thus; Maximum current of the array = 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.

Figure 1: Solar Pump

Figure 2: Solar Panels

3.3.2 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 28,000 litres, since the power supply, unlike the solar powered system, is only available on demand. The operational hours was scaled down to 5 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 additional power requirement for the motor starting 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;

Flow rate = $26m^3/5h = 5.2\ m^3/h$

The new hourly rate is thus 5.2 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. The formula reported by Ab-Aligah (2011) was used and is given as;

$$HE = \frac{Q \times H \times \rho w \times g}{3.6 \times 10^6} \qquad 7$$

Or
The formula reported by NAMREP (2006) was used and is given as;
HE = ρ x g x head x flow (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] = $9.82m/s^2$
head (H) = total dynamic head [meters] = 35m
Q = hourly flow rate [m^3/h] = $5.2\ m^3/h$
HE = hydraulic energy (kW)
Using both equations (7 and 8)
The result is; 828W (equation 7 or 8)
The hydraulic power required to pump 26000 litres of water in 3 hours is approximately 828W.
Thus, a pump rated at 828 kW (about 1.125 hp) is required for the system. For ease of procurement, a 2 hp pump is used for this system. The generator for this system is rated at 2 times the nominal power of the pump.
$Generatorpower$ = 2×828 (1.125hp) = 1.65kW(2.25hp)
Considering the mechanical loses, a 1.9 kW diesel generator was used to supply the energy required by this system.

IV. Life Cycle Cost Comparison For The Solar And Generator Powered Systems

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 3 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:

$$LCC = C_{ic} + C_e + C_m + C_{env} + C_\tau \quad (9)$$

Where: LCC =life cycle cost
Note that; 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)
$C\tau$=$ReplacementCosts$.

Table 3: Maintenance and Replacement Interval for Diesel Engine (SELF, 2008: Cost Reliability Comparison between Solar Powered and Diesel-Powered Pumps)

Maintenance andReplacement	Good quality engine (hours)	Equivalent number Of Days
Minor service (engine oil, filters, transport)	250	50
Major service (brushes, de-carbonization, 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 3 and table 4 are the detailed analysis for both photovoltaic powered pump costing and diesel generator powered pump costing

Table 3: PVPs Pump Costing (initial cost)

PV System Cost	Cost (₦)
PV Array	480,000
Pipe, Cable, Rope	300,000
Accessories (casing, gum)	150,000
Installation	200,000
Jili 4SSC3.6/138-72/1000W	950,000
Drilling	500,000
Total	**2,780,000**

Note that **$1** exchanges for **₦365 as** at the time of conducting this study

Table 4: DPs Pump Costing (initial cost)

DP System Items	Cost (₦)
1.9kW Diesel generator	225,000
2.5HP Pedrollo hydraulic submersible pump	150,000
Accessories (casing, gum)	150,000
Installation	200,000
Pipe, Cable, Rope	300,000
Drilling	500,000
Total	**1,525,000**

V. Results And Discussion

In Tables 3 and 4, the pumps have the same volume of tank as such the price of tank is not included.

Table 5. Manufactures diesel engine consumption rate (Ministry Of Mines and Energy Barrier Removal To Namibian Renewable Energy Program (NAMREP) Final Report: September 2006Feasibility Assessment for the Replacement of Diesel Pumps with Solar Pumps)

Rated Power (kw)	Litre/hour
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	2.4
Total	**1,525,000**

From the tables (3, 4, 5 and 6), the life cycle cost for diesel is calculated as

$$\text{LCCDP} = C_{ic} + C_e + C_m + C_{env} + 0 = \text{₦}\mathbf{3,375,000}$$

and that of solar is calculated as

$$\text{LCC PVP} = C_{ic} + 0 + C_m + 0 + 0 = \text{₦}\mathbf{3,280,000}$$

Table 6: Typical diesel generator maintenance and fuel costs

Maintenance and fuel	Total cost (₦)
Minor service	100,000
Major service	500,000
Overhaul	100,000
Cost of diesel	1,150,000
Total	**1,850,000**

Note that, as at the time of this research,a litreof diesel cost **₦230 ($0.63)** i.e **₦230/ltr.**
The summary of the costs for both PVP and DP is represented below

LCC
Solar Pump **₦3,280,000**
Diesel Pump **₦3,375,000**
Savings **₦95,000**
Factor: DP/PVP 1.029

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 flowrates have been considered in this work, which is the DP and the PVP. The study 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 **₦95,100**with a factor of **1.029** The high operational costs of diesel systems prevented it from being cost-effective. The outcome of this study showed that the PV pumping systems have 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 times (≥200 %)that of the solar powered unit.
It is a 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.

VI. Conclusion

This study clearly shown that the cost of solar power technology has reduced in recent times compared to years before. 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-powered water pumping systems are more cost-effective for rural areas in Nigeria than the diesel generator powered borehole systems. 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 therefore, has hihgh sustainability as compared to the diesel generator-powered system since solar powered borehole requires little periodic maintenance.

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