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Techno-economic analysis of utilizing a directly-coupled photovoltaic water pumping system for domestic application in Nigeria

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ABSTRACT

This paper presents a techno-economic application of a directly-coupled PV-pumping system for domestic application in some selected rural communities in Nigeria. Four different rural communities were considered in Ogun State, Nigeria and data of volume of water requirement per household per day were obtained through the use of interview scheduled for the rural households. The system is properly sized such that the pump energy requirement is in tandem with the PV-system of the location. Six different submersible pumps of different ratings were considered for this study. The number of PV-arrays, controllers and the tank storage capacities for various pumps were also determined. MATLAB tool is used to simulate the system. The economic assessment of the system, which includes life cycle cost, energy cost of pumps and the cubic meter cost of water were also determined. The result reveals that the life cycle cost ranges from $\$4087\ to\ \$20226$; unit cost of energy ranges from $\$0.2132\ to\ \$0.2608$; unit cost of water per cubic meter ranges from $\$0.0183\ to\ \$0.0526$ for the various submersible pumps considered. The maximum power and voltage and the efficiency of the PV module selected for the analysis are 250 W, 24 V and 14%. Also, the result also reveals that the proposed system is more cost effective than the conventional public utility water cooperation in Nigeria. The study provides the design and simulation of PV-based water pumping system, which can be used for understanding planning water supply system for rural areas.

1. Introduction

Provision of sustainable water supply has become entirely necessary not just because of its vital role in human existence, but because it has been linked to economic and industrial development, improved healthcare, improved quality and standard of living, ecosystem preservation and poverty alleviation in developing countries [1]. Lack of adequate water supply to meet the basic daily need is a major problem and can contribute to illness and death, especially in children in countries with rural communities. Naturally, as population grows, the need for water in both rural and urban areas also increases [2]. This increase in demand is impacting on the existing water infrastructure, which has made it to operate at its maximum limit [3]. Unavailability of portable water has been identified as a major factor that has induced communal clashes between rural communities in Nigeria [4]. The majority of the water scarcities noticed in the rural communities may be attributed to unstable energy source and are not due to total lack of water resources [5]. Hence, energy source is a prerequisite to sustainable water supply which is essential for life and good health.

In Nigeria, most of the rural communities are either not connected to the grid system because they are too far from the existing grid network or lack of available power supply when connected [6]. Even though the country is blessed with abundance of fossil fuel resource (Petrol/diesel), transporting this fuel to most rural areas to meet energy needs is also a problem because of no existing road infrastructure in most rural communities in Nigeria [7]. Historically, most rural communities in Nigeria suffer acute water scarcity even when groundwater availability is in abundance. This groundwater availability requires reliable energy source for it to be pumped to the required surface were it can be easily utilized. Therefore, the other widely used alternative is to use fossil fuel generator which are environmentally not friendly and with a high operating cost due to fuel cost and frequent breakdown. Using renewable energy as an alternative energy source is gaining attraction for water pumping systems in many remote area locations across the globe [8]. Nigeria has been identified as a country with abundance solar energy resources [9]. Solar energy is clean, economic disaster and water contamination free (unlike fossil fuel), etc. Utilizing solar energy to pump water will reduce the hazard of fossil emission pollution and help provide a lasting solution to frequent water scarcity in rural communities in Nigeria. Proper sizing of the PV-system is required for reliable economic benefit.

The possibility of utilizing PV-powered water-pumps in Nigeria has been slightly discussed in the literature. Allouhi et al. [10] presented a performance comparison of utilizing directly-coupled photovoltaic water pumping system and a MPPT DC-DC PV-water system for domestic use in a remote location in Morocco. The results revealed that the MPPT DC-DC PV-system requires a smaller number of PV modules and is more economical compared to the directly-couple system. The benefit of using solar powered water pumping system for groundwater in Nigeria was also studied [11]. The result shows the design procedure and economic implication. An investigative experimental study to know the performance of direct-coupled solar DC-pump was done by authors in [12]. The experiment was conducted with two static head configuration pumps and varying solar radiation. The result shows that the system is suitable for a small irrigation system rather than grid-connection. The effect of total head and solar radiation on PV-water pumping system was studied by authors in [13]. The result reveals the best system head suitable for a helical submersible rotor pump considered for the study. The possibility of also utilizing solar energy source to pump groundwater in Saudi Arabia was also investigated [14]. The result also proves the effectiveness in the use of solar energy in groundwater utilization.

While all the aforementioned studies were focused on designing a solar powered water-pump, this present work goes a step further in identifying the most suitable pump for a particular rural community in Nigeria. In this paper, some rural household communities were selected based on their potential for population growth and availability of data and Ogun state was chosen due to its proximity to the commercial hub of Nigeria (Lagos State) and a link between Nigeria to another country. The output of this paper would be very important because it would inform policy makers, Government officials and possible investors at alleviating the suffering caused by lack of portable water in rural communities in Nigeria which will ultimately impact positively on the well-being and health of the rural dwellers.

2. Methodology

The selection of a suitable submersible pump requires a proper estimation of water needs of the targeted rural communities. This precedes the sizing of the required PV system and the economic

analysis.

2.1 The Description of Study Locations

The rural areas chosen for this study are located in Iwoye-Ketu communities, Odeda Communities, Ogun waterside and Obafemi Owode. Fishing and farming is the main predominant of the people in the rural communities chosen. Fig. 1 shows the locations of the study area on Ogun State map of Nigeria. Data of daily water requirements of each household in the communities were obtained through the use of interview schedule (questionnaire). Table 1 depicts the number of household per rural community.

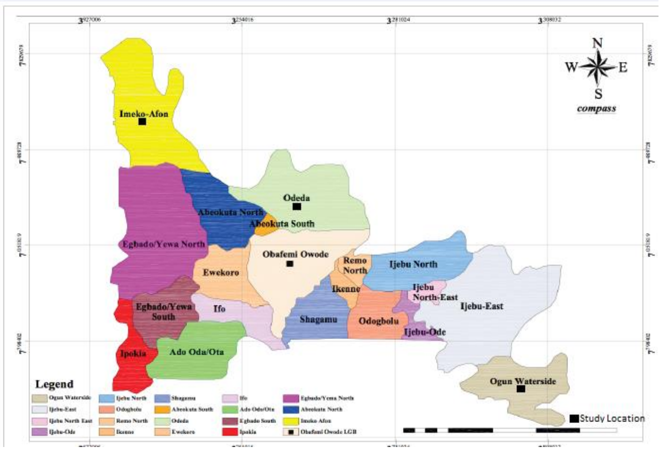

Fig. 1. Ogun state map of Nigeria, showing the study area [15]

Table 1

Data of the Study Area

Description of rural communities	Number of Household
Iwoye-Ketu	80
Odeda	130
Waterside	125
Obafemi Owode	200

2.2 *Selecting a Submersible Pump*

The rating of a pump is estimated by proper matching of the total head (h_{sys}) and discharge rate of the pump with the best efficiency of pump. The system head is given by [16]:

$$h_{sys} = h_{hpf} + h_{hf} + h_{hve} \tag{1}$$

where; h_{hpf}, h_{hf} and h_{hve} represents head loss as a result of pipe friction, the head loss due to fittings and vertical elevation of the pipe from the submersible pump respectively.

The power required to deliver water from underground to a required head is [17]:

$$P_w = \frac{\rho g h_{sys} Q}{\eta} \tag{2}$$

where; ρ, g, Q and η represents the density of water ($1000 kg/m^3$), acceleration due to gravity ($9.81\ m/s^2$), discharge rate (m^3/h) and pump efficiency (0.65) respectively.

Assuming a household requires 162 litres of water per day [18], with an average sunshine hour of 6 hours per day. The site discharge rate can be expressed as [16]:

$$Q = \frac{162 \times h_h}{t} \quad (L/h) \tag{3}$$

where, h_h and t represents the number of household and sunshine hour per rural community. All pump models has a unique system of head-discharge rate curves, in which a suitable pump may be selected. Fig. 2 shows the pumps considered for this study.

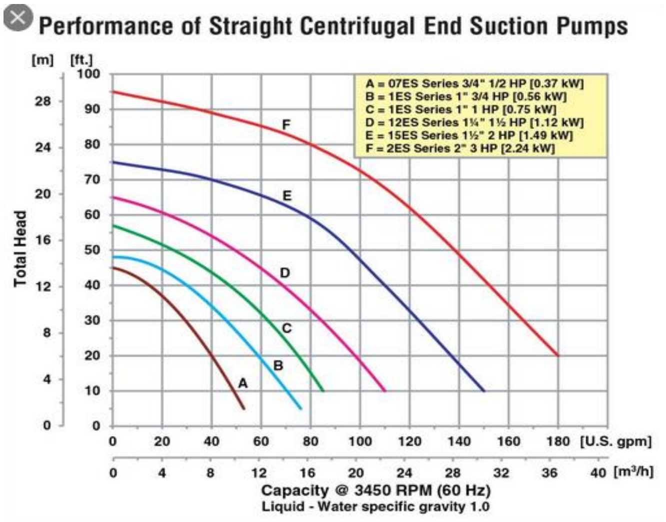

Fig. 2. Pump chart for ES model pump

2.3 *Selection of Suitable PV-Array*

The PV-array is usually in the form of wattage and voltage. It is a standard practice to multiply the pump power by a factor (1.2) in order to compensate for under sizing [17]. The solar array power required is given by [17]

$$P_{pV-array} = \frac{1.2 \times pump\ wattage\ (P_w)}{\eta_{pv}} \tag{4}$$

Where; η_{pv} is the efficiency of the PV-module (0.14).

Table 2

Characteristics of the selected PV-module [22]

Parameters	Ratings
Maximum power	250 W
Short-circuit current	8.17 A
Maxim power voltage	24 V
System module voltage	24 V
PV-array efficiency	14 %

The number of PV-array required to be connected in series is given by [19]:

$$NS_{s-array} = \frac{system\ voltage\ (V_s)}{Array\ normal\ voltage\ (V_a)} \tag{5}$$

The number of PV-array required to be connected in parallel is given by [19]:

$$NP_{p-array} = \frac{P_{pv-array}}{NS_{s-array} \times P_m} \tag{6}$$

Where; P_m is the unit array power.

The total number of PV-array required is given by [19]:

$$NT_{p-array} = NS_{s-array} \times NP_{p-array} \tag{7}$$

2.4 Sizing of The Controller

The main function of a controller is to maintain the voltage between the PV-array and the DC pump, i.e. protect the pump from overvoltage. The rated capacity of the controller is given by [20]:

$$I_{rating} = 1.25 \times I_{sc} \times NP_{p-array} \tag{8}$$

Where; I_{sc} is the short-circuit current of the PV-array and 1.25 is the safety factor. The extra 25% capacity is used to cover for over-current from the solar module. The selected controller is $24V, 100A$.

The number of parallel controller required is given by [20].

$$NC_p = \frac{I_{rating}}{unit\ ampere\ per\ controller} \tag{9}$$

2.5 Sizing of Tank

Tanks are mainly used to store water in Nigeria, unlike electricity in batteries, thereby reducing the overall cost and complexity of the system. The volume of the storage tank depends on the daily water needs and the number of autonomy. The volume of the storage tank is given by.

$$V_{tk} = 162 \times h_y \times D_{au} \tag{10}$$

Where; h_h, D_{au} are the number of households and the autonomy days, respectively. The number of autonomy days is 3 in this paper.

2.6 PV-Pumping Arrangement System

The configuration of PV-pumping system adopted in this work is directly-coupled system. In this arrangement, the output of the PV-array is directly fed into the DC submersible pump. A controller maybe connected between these two components in order to serve as a protective device. The advantage of a directly-coupled system is that it needs no energy storage device like battery, which is more capital intensive compared to a storage tank of water used in it replacement for storing water. The directly-coupled PV-pumping system is shown in Fig. 3.

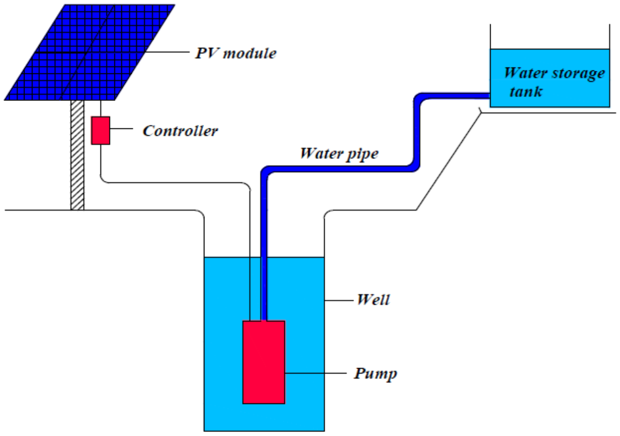

Fig. 3. Directly-coupled PV-pumping system [21]

2.7 Economic Assessment of a Unit Cost of Water

The motive behind a PV-powered water system is to achieve a reduced cubic meter cost of water. The economic study involves determining individual components cost that makes up the system such as investment cost (PV-array, controller, installation, civil works, item delivery, cable and borehole, DC pump, etc.), operations and maintenance cost and replacement cost of the DC pump. The life cycle cost (LCC) of a PV-pump system over a life cycle of 20 years can be determined as [22]:

$$LCC_{pv-pump} = C_i + C_m + C_r \tag{14}$$

Where; C_i, C_m and C_r represent the investment cost, operation and maintenance cost and replacement cost respectively. The operations and maintenance cost is assumed to be 0.1% of investment amount and is given by [16]:

$$C_m = C_{opm} \times \left[\frac{1+i}{d-i}\right]\left[1 - \left(\frac{1+i}{1+d}\right)^n\right] \tag{15}$$

Where; C_{opm} is assumed to be 0.1% of investment cost, i is rate of inflation (8.4%), d the rate of discount (11%), r is rate of interest (15%) based on [22]. Also, n is the project life time. The replacement cost is given by [16]:

$$C_r = C_{icp}\left[\frac{1+r}{1+d}\right]^n \tag{16}$$

Where; C_{icp} is the initial cost of pump.

The pump is the only component considered for replacement in every 8 years. It is sometimes necessary to evaluate the LCC of a system on an annual level. The annualized LCC (ALCC) of a PV- pump system can be estimated as [17].

$$ALCC_{sys} = LCC_{pv-pump}\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{n}}\right] \quad (17)$$

The unit cubic meter cost of water(C_{water}) is thus evaluated as [18].

$$C_{water} = \frac{ALCC_{sys}}{Q_{wd}\times 365} \quad (18)$$

Where; Q_{wd} is the quantity of water produced per day.

The unit cost of energy for each pump is given by [19].

$$COE_{pump} = \frac{ALCC_{sys}}{1.2\times p_{w}\times t\times 365} \quad (19)$$

Where; '1.2' is a safety factor in case of unaccounted load or future expansion and t is the daily hours of operation of pump.

After local market survey and literature review, the following are the assumptions made regarding prices of components.

Table 3

Technical and cost parameters of components

Description of items	Unit cost ($)
PV Array (250W, 24V)	150
Solar controller (100A, 24V)	300
Cost per PV installation + civil works + item delivery (10% of PV-array)	–
Cost of DC Pump (1HP)	37.5
Cost of cables per PV-Array	3.75
Cost of storage Tank per cubic meter	2.5
Cost of bore-hole	625

3. Results and Discussion

In this section results are presented and discussed under different sub-headings of this section. Section 3.1 presents the different submersible DC pumps considered across the various rural communities. The different components that makes up the solar system is discussed in section 3.2 while section 3.3 presents the economic aspect of the PV-pumping system.

3.1 Determination of System Head and Discharge Rate of Submersible Pump

Choosing a suitable submersible pump will depend on the estimation system head (h_{sys}) and corresponding discharge rate of the pump, while is expected to suit the volume of water requirement per day for each locations. Eq. 3 reveals the range of Q for the different locations. From Table-1 and Eq. 3, the least discharge rate for the four locations considered is $2.2\,m^3/h$, which correspond to 12.6m head (h_{sys}) for Pump-A in Fig.-1. Hence, a uniform head of 12.6m is assumed for all submersible pump considered. This head (12.6m) correspond to $5.2\,m^3/h$, $8.8\,m^3/h$, $13.2\,m^3/h$, $21.6\,m^3/h$ and $30.5\,m^3/h$ for pump A, B, C, D, E and F respectively based on the pump curve chart of Fig. 1. The selection of the system head (h_{sys}) was done such that at least one pump will be suitable for at least one rural community. Table-4 depicts a summary of the result of pump suitability for each locations considered

Table 4

Summary of pump suitability for each location

Location	Iwoye-ketu					
Pump	A	B	C	D	E	F
Location	Odeda					
Pump	B	C	D	E	F	
Location	Waterside					
Pump	B	C	D	E	F	
Location	Obafemi Owode					
Pump	C	D	E	F		

From the table, submersible pumps 'A', 'B','C','D','E' and 'F' are suitable for Iwoye-ketu community, all pumps except 'A' is suitable for Odeda and Waterside communities, and all pumps excepts 'A' and 'B' are suitable for Obafemi owode community based on their water productions per day.

3.2 Determination of Components that Makes up the PV-pump System

Based on the ratings of the submersible pump and the solar radiations of the locations, the required PV-array rating, number of PV-arrays, number of controllers and storage tank capacities were determined for each submersible pump. Table 5 presents a summary of the PV-pump system components. The PV-array capacity$(P_{pv-array})$ ranges from 3.17kW for Pump-A to 19.20kW for Pump-F. The total number of PV-array required$(NT_{pv-array})$, ranges from 13 for Pump-A to 77 for Pump-F.The total number of controller needed(NC_{p}), ranges from 2 for Pump-A to 8 for Pump-F. Table 3 reveals that pump model 'A' has the least $P_{pv-array}$ (3.17kW) and $NT_{pv-array}(13)$ while pump model 'F' has the highest $P_{pv-array}$(19.20 kW), $NT_{pv-array}(77)$ and $N_{cp}(77)$.

Furthermore, pump model 'A' has the least storage tank capacity, while, pump model 'F' has the highest storage capacity.

Table 5

Determination of PV-pump components value

Pump Model	$P_{pv-array}$ (kW),	$NT_{pv-array}$	NC_p	Tank Storage Capacity
A	3.17	13	2	$39.6m^3$
B	4.80	20	2	$93.6m^3$
C	6.43	26	3	$158.4m^3$
D	6.43	39	4	$237.6m^3$
E	9.60	51	6	$388.8m^3$
F	19.20	77	8	$549m^3$

3.3 Economic Evaluation of a PV-Pumping System

The economic comparison of the different submersible pump model for $LCC_{pv-pump}, COE_{pump}, C_{water}$, Initial investment, O and M and C_r are resented in Table 6.

Table 6

Economic comparison of PV-pump model

Pump Model	A	B	C	D	E	F
C_{water} (\$)	0.0526	0.0306	0.0236	0.0225	0.0183	0.0188
COE_{pump} (\$/kWh)	0.2608	0.2369	0.2309	0.2206	0.2211	0.2132
$LCC_{pv-pump}$ (\$)	4087	5619	7334	10465	13957	20226
Initial investment (\$)	3532	4855	6337	9042	12059	17475
O and M cost (\$)	556	764	997	1423	1898	2751
C_r (\$)	43.86	64.88	86.89	129.75	172.62	259.51

From the Table, the $LCC_{pv-pump}$ ranges from \$4087 for pump 'A' to \$20226 for pump 'F', while COE_{pump}ranges from \$$0.2608/kWh$ for pump 'A' to \$$0.2132/kwh$ for pump 'F'. Also, from Table 4, Pump 'E' has the least cost per cubic meter of water of \$0.0183, hence, Pump 'E' is selected as the best pump among other pumps to be considered. The cost of the cubic meter of water across all the submersible pumps is low, this is as a result of using the storage tank against the high initial and replacement cost of battery. Again, it can be deduce that the PV-system pump model with the least initial investment cost (Pump 'A') is not necessarily the system with the least cubic meter cost of water (Pump 'E') and energy (Pump 'F'). The cubic meter cost of water for all the submersible pump models are very much lower than the public rate in Nigeria, which is in the range\$0.36 − 0.6 per cubic meter [16]. Hence, PV-pumping system is more economical compared to the public utility water cooperation agencies in Nigeria.

Fig. 4 and 5 below, depicts the cost per cubic meter of water and cost of energy for various pump models considered.

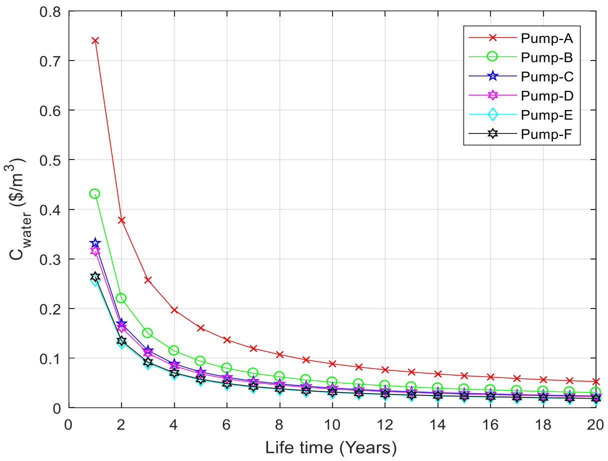

Fig. 4. Cubic meter cost of water for different pumps

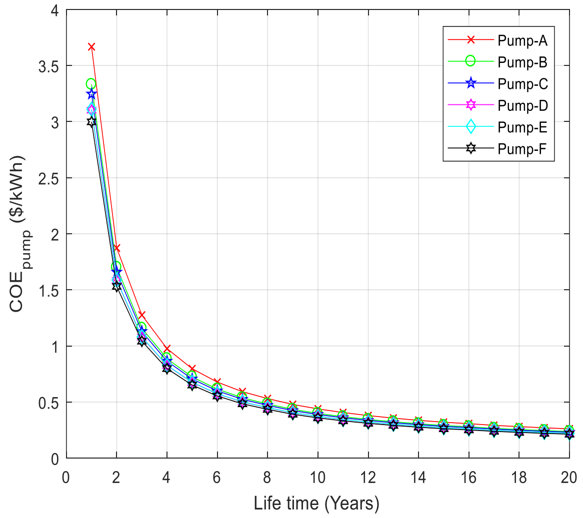

Fig. 5. Energy cost for different pumps

From the Fig. 4, the cubic meter cost of water and the energy cost of the pumps decreases exponentially with life time of the project. It can be concluded from the above Fig. 5 that the cost per cubic meter of water and energy cost of pump decreases sharply from the beginning of the year than later part of the year. This is as a result of lower operations and maintenance cost compared to investment cost of project during lifetime.

4. Conclusion

This study presents a detailed techno-economic selection of a suitable submersible pump for PV-water pumping system in some selected rural communities in

Ogun State, Nigeria. The study utilizes data of rural household water requirement across four rural locations in Ogun State, Nigeria and considered six different DC submersible pump model of different ratings. Based on the results obtained from the study, the following can be concluded.

- The quantity of water required are$12.96m^3$, $21.06m^3$, $20.25m^3$ and $32.40m^3$ per day for Iwoye-ketu, Odeda, Waterside and Obafemi owode location respectively.
- The selected system head (12.6m) is suitable to provide the least volume of water required per day of $12.96m^3$ with pump ‘A’ for Iwoye-ketu.
- The unit cost per cubic meter of water per day ranges from $\$0.0183$ for pump ‘E’ to $\$0.0526$ pump ‘A’.
- Pump ‘E’ is selected as the best pump suitable for all the locations because of its least cost per cubic meter.
- PV-pumping system is better economically compared to the usual public utility water cooperation in the country.
- Lower initial investment cost is not a guarantee for lower cubic meter cost of water and energy.

This study utilizes the cost benefit of storage tank against the high cost of battery for a PV pumping system. The outcome of this study will be useful for experts in the area of rural water resources and Government agency for policy formulation in the area of basic social amenities for rural communities in Nigeria and beyond.

Declaration of Competing Interest and Funding

The authors of this work certify that no conflict of interest is associated with this manuscript and that this work has received no funding.

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