Solar-Powered Groundwater Pumping Systems for Nigerian Water Sheds

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Abstract- The paper presents an overview of the occurrence of different groundwater sheds, water quality, and availability in Nigeria. It also discusses the viability of solar-powered groundwater pumping systems in Nigeria. Applicable methods for system design and economic analysis are further outlined.

Keywords- PV water pumping, Nigerian water sheds

1. Introduction

The design of a solar-powered groundwater pumping system for a locality requires a knowledge of the hydrogeological characteristics of the underlying aquifer (such as the aquifer depth and borehole yield), the output water quality, as well as the local solar radiation intensity data (including the hourly and monthly variations).

Having obtained the foregoing information, the system design entails determining the water demand and, hence the required storage capacity, rating and selecting a suitable submersible pump, sizing the photo-voltaic array, sizing the energy storage battery and rating the inverter.

This paper outlines the design data for application in Nigeria, and useful methods and procedures for system design and economic analysis.

2. Identification of Groundwater Sheds in Nigeria

Groundwater occurrence in Nigeria has been classified into eight hydrogeological areas, together with local groundwater in shallow alluvial aquifers adjacent to major rivers, as follows [1]:

a. The Sokoto Basin Zone which comprises sedimentary rocks in Northwestern Nigeria. An unconfined aquifer occurs at a depth of 15 – 75m and a confined aquifer occurs at 75 – 100m with artesian conditions. Yields range from below 3.6 to 20 m^3/h.

b. The Chad Basin Zone which comprises sedimentary rocks. Three main aquifers had been identified here: an upper aquifer at 30 – 100m depth (at the eastern part of the basin), a middle aquifer occurring from a 230m depth near Maiduguri, and a lower aquifer at a depth of 425 – 550m. Borehole yields are between 4.3 and $5.8m^3/h$ from the upper unconfined aquifer and 5.9 to $7.6m^3/h$ from the middle aquifer. Over-exploitation of the aquifers in the Chad Basin has led to a recent decline in groundwater level and has necessitated drilling to greater depths in order to access the lower aquifer.

c. The Middle Niger Basin Zone which comprises sandstone aquifers yielding between 2.5 and $20.0m^3/h$ and the alluvium on the Niger Valley yielding between 27.0 and $35.0m^3/h$.

d. The Benue Basin Zone which is the least exploited basin in Nigeria extending from the Cameroon border to the Niger-Benue confluence. The unconfined sandstone aquifers in the area yield between 3.6 and $30.0m^3/h$.

e. The South western Zone which comprises sedimentary rocks bounded in the south by the coastal alluvium and in the north by the Basement Complex. The sedimentary rocks in this zone have been classified as consolidated sediments and unconsolidated sediments [2]. The consolidated sediments contain only minor aquifers. Their particle size is small and so permeability is limited. Borehole depths in the consolidated sediments vary from 10m to 60m with yields in the range 0.5 to 1.2m^3/h.

The unconsolidated sediments incorporate sandy horizons which constitute viable aquifers, usually unconfined. In the Lagos area, for instance, there are two major aquifer systems of the unconsolidated nature: the Tertiary Coastal Plains Sands aquifer and the Cretaceous Abeokuta formation. The former is encountered at 60 to 100m. The Abeokuta formation is encountered at a depth of about 800m in the Lagos area. It constitutes a prolific aquifer with a yield of the order of 300m^3/h. However, the great depth at which it occurs indicates it is only utilized by the big industries and government water supply agencies.

f. The South-Central Zone which is made up of Cretaceous and Tertiary sediments centred on the Niger Delta. Yields are from 11.0 to 25.0m^3/h.

g. The South-Eastern Zone which comprises Cretaceous sediments in the Anambra and Cross River basins. There is an abundance of alluvial aquifers and surface water resources in this zone.

h. The Basement Complex which comprises over 60 percent of the country's area. It consists of low permeability rocks and groundwater occurs in the weathered mantle and fracture zones with yields between 3.6 and 7.2 m^3/h. Depths of drilling for these aquifers hardly exceed 60m.

It has been mentioned [2] that the poor hydrogeological properties of some areas of the Basement Complex formation, saline intrusion in the coastal areas, great depths of occurrence, and the predominance of impermeable shales and clays in some areas of the Sedimentary formation are some of the impediments to groundwater development in the country.

The development of a suitable method for the exploitation of the groundwater resources of a given area requires the study and identification of the hydrogeological characteristics of the underlying aquifer(s). Generally, following from the foregoing discussions, the exploitable aquifer depths in Nigeria vary widely from about 10 to 800m while borehole yields vary from 0.5 to 300m^3/h.

3. Groundwater Quality

The quality of groundwater in the country is generally good. Only in some areas are iron, nitrate and fluoride concentrations above World Health Organization (WHO) standards[3]. In about 20% of the country the groundwater has low pH (< 6.5) and the water is very corrosive in those localities, and this affects the choice of borehole lining material. In about 40% of the country, the water is moderately corrosive with pH of 6.5 to 6.8, while in the remaining 40% the pH is higher and the water is not corrosive [3].

The groundwater in some of the areas underlain by the consolidated sediments of the Benue Basin tend to be high in dissolved solids [2]. In Awe and Keana in Nassarawa State and in Abakaliki in Ebonyi State the groundwater is saline, rendering it unusable [2]. Also, many shallow aquifers of the coastal belt are prone to saline invasion from sea water. The presence of arsenic has also been reported in the groundwater in some parts of Benue State [2].

Furthermore, several researchers [4, 5, 6, 7] have shown in various studies that the country's shallow aquifers are potentially vulnerable to pollution from agricultural sources (such as fertilizers), domestic sources (such as waste dumps and latrines) and industrial sources (such as oil and petrochemical spills) except where surface layers are of poor permeability and afford some protection of the underlying aquifers.

The foregoing water quality issues indicate the need for proper laboratory analyses for every water borehole output, so that appropriate treatment methods may be designed.

4. Water Demand in Nigeria

The water demand is an aggregate of the different water uses (ie. domestic, agricultural and industrial). Total annual water use in Nigeria was estimated at 8km^3 for the year 2000 [8]. Agriculture (mainly irrigation) was estimated as the biggest water user with 5.5km^3 (or 69% of total use), followed by the domestic sector with about 1.7km^3 (21%) and industry with 0.8km^3 (10%).

Nigeria's annual extractable groundwater resources are about 59.51 km^3, distributed as follows: 10.27km^3 in Northern Nigeria, 25.48km^3 in the Middle Belt, and 23.76km^3 in the South [8]. Groundwater resources are, therefore, abundant in Nigeria, being in far greater availability than the demand. Apart from groundwater, the other water resource (which is in more abundance than groundwater) which adds to the total water availability is surface water (in rivers, seas, lakes, etc).

For a groundwater pumping scheme, a good estimate of the water demand is necessary in order to achieve a reliable system performance. For domestic water use, various per capita figures had been recommended, and the adopted data should depend on such factors as the average standard of living of the populace, availability of the water resource and prevailing climatic conditions. The British Standards Code of Practice (CP) 310 recommends a minimum of 90 L/person/day for dwellings [9], while the Building Officials and Code Administrators, Inc. in the USA recommend a minimum of 190L/person/day (i.e. 50 US gallons) [10]. Also, for rural households using public hydrants in streets, Postel [11] had recommended 20 to 70L/person/day.

Table 1. Approximate Water Use for Household and Agriculture

Application	Approximate Usage
Household	50 gallons per day per person (average)
Cattle and Horses	10 – 15 gallons per day per head
Dairy Cows	20 – 30 gallons per day

Sheep and Goats	2 gallons per day
Small Animals	¼ gallon per day per 25lb body weight
Poultry	6 – 12 gallons per day per 100 birds
Young Trees	15 gallons per day in dry weather

For livestock watering and tree growing, guidelines have also been provided to approximate water demand. An example of such guidelines is Table 1 [12].

5. Viability of Solar-Powered Groundwater Pumping Systems in Nigeria

Photo-voltaic (PV) water pumping systems have the advantages (over conventional pumping systems such as those which use fossil fuels) of being of low maintenance, easy to install, simple and reliable, incurring no fuel costs or spills, and requiring unattended operation most of the time [12, 13, 14]. The reliability of PV pumping systems is such that 20 to 25 year power warranties are typical, with life expectancies beyond 30 years [12]. Furthermore, the prevailing electricity supply situation in Nigeria, where many rural communities are not yet connected to the National Electricity Grid, requires the utilization of alternative energy sources for such communities.

The main setback in the utilization of solar energy, however, is that energy output is low in cloudy weathers and that it is unuseable during night time. To improve on this setback, storage batteries are usually incorporated in solar-powered pumping systems.

Nigeria's geographical location between latitudes 4° and 14° North of the equator endows her with enormous solar energy resources. The yearly average solar energy received on a horizontal surface in Nigeria is 2300 KWh/m^2 [15], and annual averages of global solar radiation as high as 7.0 KWh/m^2/day have been recorded [16].

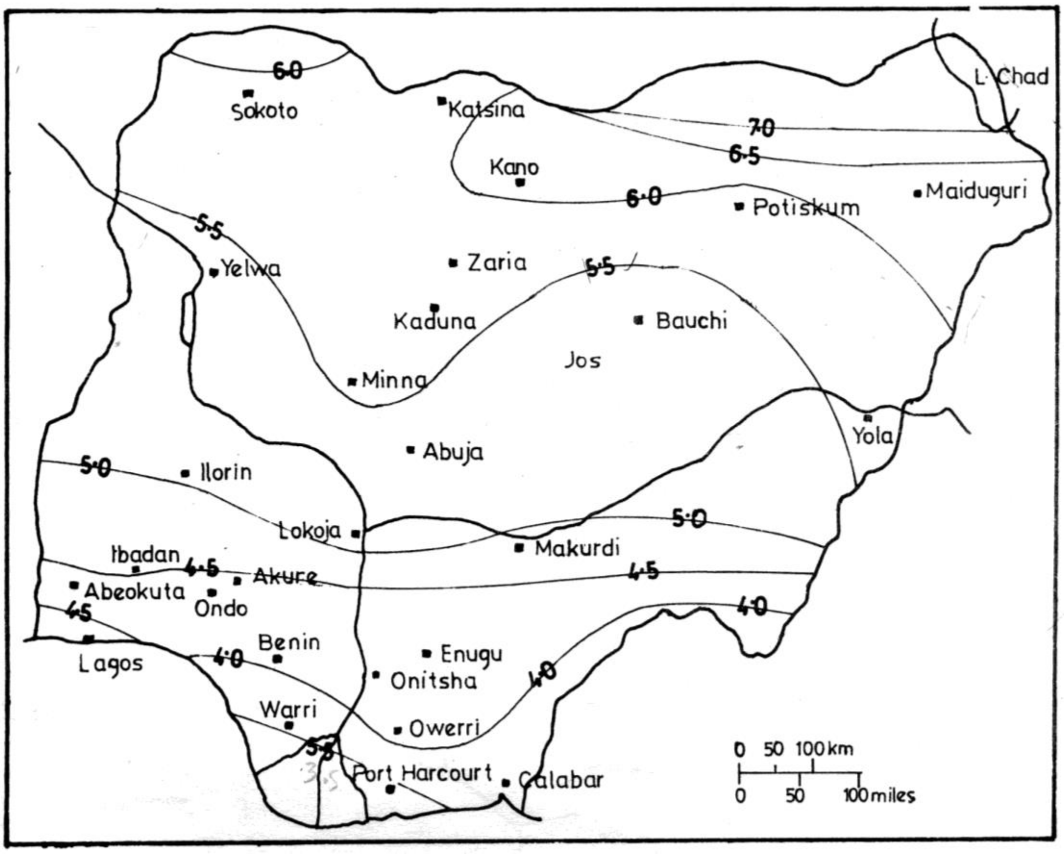


Fig. 1. Annual Average of Global Solar Radiation in Nigeria, kWh/m^2/day

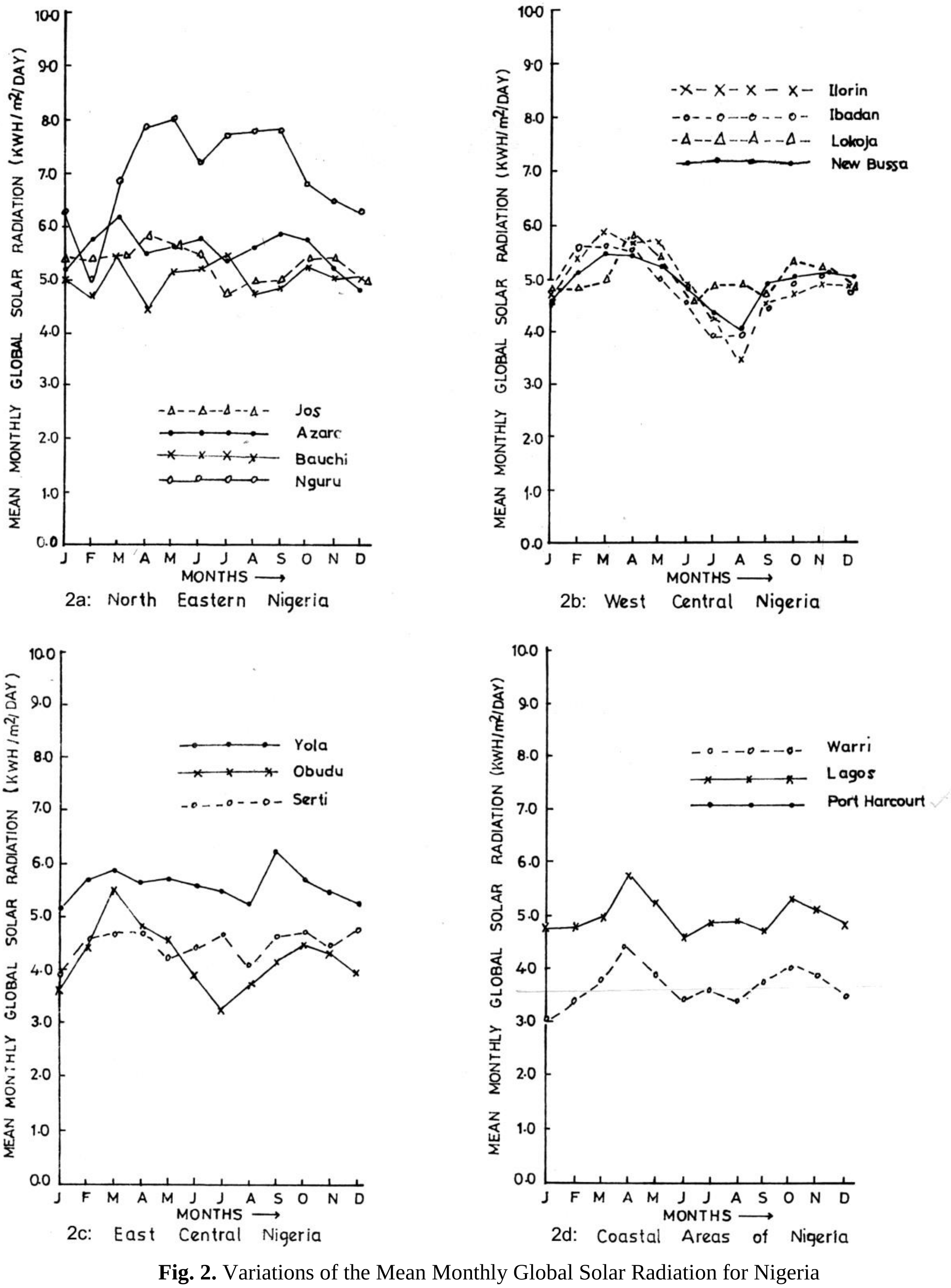


Fig. 2. Variations of the Mean Monthly Global Solar Radiation for Nigeria

The geographical distribution of the annual average global radiation in Nigeria is depicted in the iso-radiation map of Fig. 1 [16]; while the monthly variations of mean global radiation for some measurement stations are presented in Fig. 2 [16]. Also, the monthly mean daily sunshine hours for some stations for a period of 35 years, as recorded by the Nigerian Building and Road Research Institute [16] are shown in Table 2 while the annual averages of daily sunshine hours are given in the map of Fig. 3. [16].

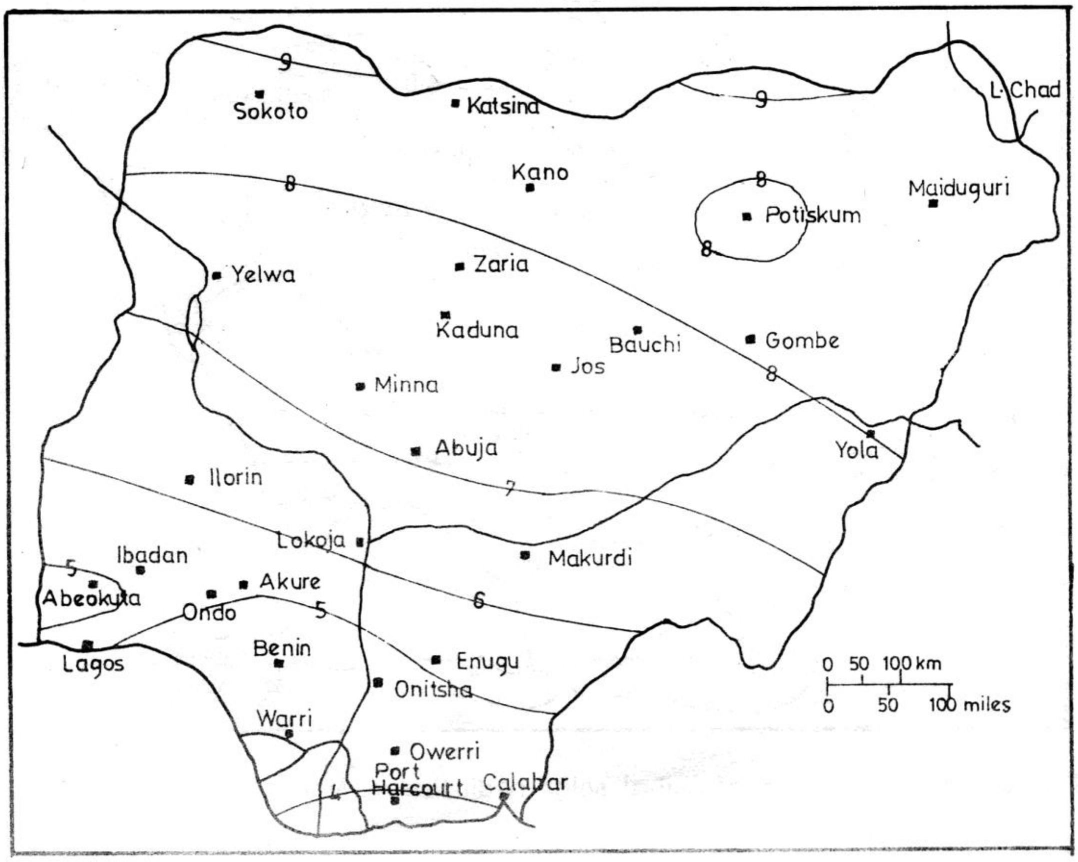
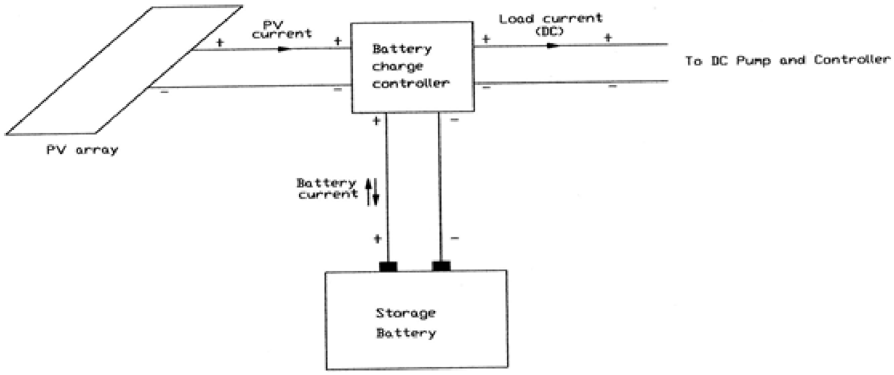


Fig. 3. Annual Average of Daily Sunshine Hours in Nigeria (1951 - 1985)

Table 2. Monthly Mean Daily Sunshine Hour (1951 – 1985) in Nigeria

S/NO	STATION	JAN.	FEB.	MAR.	APR.	MAY	JUN	JUL	AUG	SEP.	OCT.	NOV.	DEC.	AVE
1.	Abeokuta	5.00	5.35	5.35	5.55	5.90	4.30	3.03	2.15	3.05	4.15	5.73	6.00	4.65
2.	Akure	6.52	5.86	6.30	6.37	5.30	4.24	2.74	2.65	3.50	4.83	6.37	6.40	5.09
3.	Baddeggi	7.88	8.18	7.66	7.13	7.63	7.02	5.05	3.78	5.62	8.12	8.96	8.84	7.16
4.	Bauchi	9.10	9.0	8.24	7.23	7.73	6.98	6.90	6.12	7.10	8.74	9.46	9.32	7.99
5.	Benin City	5.90	6.07	5.57	5.55	6.03	4.70	2.91	2.56	3.0	4.61	6.06	6.60	4.96
6.	Bida	7.35	6.77	6.2	7.10	6.62	5.40	4.50	4.10	5.30	6.80	7.20	7.40	6.23
7.	Calabar	5.40	5.20	4.54	5.10	4.92	4.24	2.74	1.90	2.27	3.62	4.96	5.76	4.22
8.	Enugu	6.90	6.70	5.25	5.83	5.94	5.37	4.15	3.72	3.71	5.36	7.23	7.20	5.61
9.	Ibadan	6.32	7.05	6.09	5.60	6.37	5.11	3.44	2.70	3.10	5.63	6.80	6.84	5.42
10.	Ibi	7.51	7.60	7.82	7.80	7.10	5.70	4.30	5.20	5.60	7.00	7.90	6.20	6.81
11.	Ikom	5.40	5.73	5.24	6.27	5.20	4.25	2.55	1.90	2.80	4.50	5.20	7.10	4.68
12.	Ilorin	7.41	7.61	7.28	5.71	7.19	6.70	4.91	3.59	4.22	6.56	7.80	7.68	6.47
13.	Ikeja	6.13	6.92	6.05	5.91	5.80	3.46	2.43	3.06	3.36	5.28	6.27	6.38	5.09
14.	Jos	9.40	9.34	8.30	6.97	6.47	6.73	5.01	4.48	5.73	8.09	9.82	9.86	7.52
15.	Kaduna	9.20	9.10	8.10	7.83	8.0	7.66	5.91	5.09	6.35	8.18	9.33	9.26	7.83
16.	Kano	8.52	8.47	8.02	8.29	8.89	8.78	7.69	6.75	7.87	3.47	8.82	8.51	8.26
17.	Katsina	9.45	9.10	8.60	8.10	8.70	7.98	9.96	7.30	8.61	9.50	9.56	9.83	8.72
18.	Lagos	5.70	6.33	6.65	6.65	5.63	4.42	3.64	3.84	4.54	6.02	6.84	6.74	5.58
19.	Lokoja	7.06	7.01	6.90	6.42	6.52	5.40	4.18	5.55	5.15	6.57	7.80	9.47	6.50
20.	Maiduguri	9.34	9.44	8.91	8.47	8.37	8.62	7.20	6.53	7.48	9.12	9.43	10.0	9.34
21.	Makurdi	7.70	8.01	7.30	6.83	6.96	6.40	4.90	4.46	4.85	6.79	8.15	8.40	6.73
22.	Minna	8.60	8.50	8.05	7.33	7.84	6.12	5.16	4.35	6.25	8.23	9.15	9.20	7.40
23.	Nguru	8.95	7.85	7.70	8.10	9.10	8.00	7.45	8.68	8.05	9.10	9.00	9.3	8.44
24.	Ogoja	7.10	6.37	5.97	7.13	6.27	5.20	3.50	2.70	4.10	5.94	6.60	7.17	5.67
25.	Ondo	7.24	6.62	5.76	5.60	5.56	4.85	3.05	2.58	2.95	5.01	6.54	6.78	5.21
26.	Oshogbo	6.81	6.90	7.14	6.27	6.70	5.73	3.64	2.55	3.44	5.83	7.34	7.54	5.82
27.	Owerri	5.45	5.54	5.20	5.00	5.10	2.95	2.75	2.15	3.00	4.10	5.40	5.85	4.37
28.	Onitsha	4.74	5.30	5.45	6.54	5.60	4.66	3.37	2.77	3.30	5.50	5.94	6.20	4.87
29.	Port Harcourt	4.79	5.0	4.15	4.58	4.50	3.13	2.09	2.59	2.20	3.14	4.70	5.30	3.85
30.	Potiskum	8.50	9.15	7.10	8.25	7.75	7.20	6.40	6.20	7.40	8.52	8.20	9.35	7.84
31.	Sokoto	9.15	9.10	8.83	6.62	8.67	9.00	8.10	7.42	8.28	9.28	9.60	9.43	8.79
32.	Warri	5.62	5.58	4.98	4.85	5.11	3.53	1.93	2.80	2.41	4.27	5.64	5.89	4.38
33.	Yola	9.06	8.81	8.38	9.17	8.03	8.06	6.72	6.09	6.73	8.72	8.74	9.42	4.46
34.	Yelwa	8.42	7.81	7.34	7.91	7.53	7.15	6.82	5.54	7.35	8.23	6.94	8.52	7.46
35.	Zaria	9.15	8.10	7.5	7.9	8.5	7.6	6.15	6.4	7.20	8.20	8.55	9.10	7.86



(a)

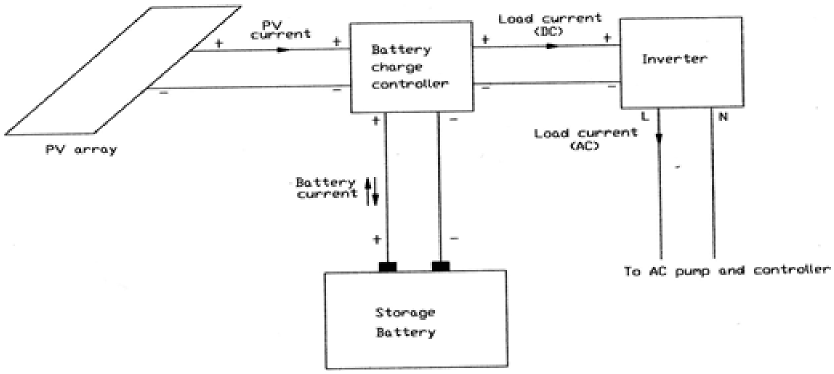


Fig. 4. a: PV System Incorporating a Battery and Charge Controller to Produce DC, b: PV System Incorporating an Inverter to Produce AC

6. Design Parameters of Solar-Powered Groundwater Pumping Systems

The design parameters of a typical solar-powered groundwater pumping system (illustrated in Fig 4a and 4b) are described as follows:

6.1. Solar Energy Data

For solar pumping systems which incorporate energy storage batteries, the relevant solar radiation data for system design is the average daily solar energy input G_{av} on a south-facing surface tilted at an angle equal to the site latitude for locations in the Northern Hemisphere such as Nigeria [17,18], this data being used in conjunction with the storage capacity of the battery. When batteries are not used, the required data is the average solar energy input for the sun hours on a south-facing surface titled of an angle equal to the site latitude [17, 18], and the number of sunshine hours.

6.2. Submersible Pump Rating and Power Requirements

The pump rating procedure, as elaborated in literature [19 – 23] requires two important criteria, namely the discharge rate and the total system pressure which the pump is expected to overcome in duty.

6.2.1. System Pressure

The discharge rate of the selected pump should be in the region of the desired rate of filling up the storage capacity, while the total system pressure of a submersible pump comprises of the following:

(a) The vertical depth, below ground, of installation of the submersible pump. This depth is determined by such factors as the depth of the useful underground water bearing stratum (the aquifer) in the locality and the dynamic water level established as the lowest well water level during a draw-down pump test, as described in literature [24, 25].

(b) The vertical elevation, above ground, of the discharge pipe to the storage reservoir.

(c) Pressure loss due to pipe friction. This loss is due to the resistance to fluid flow caused by the internal surface of the pipe. It is related to a friction factor f of the internal pipe wall as [19]

$$hp = \frac{4fl}{d}\frac{v^2}{2g} \tag{1}$$

where h_p = lost head (m)

l = pipe length (m)

d = pipe internal diameter (m)

v = flow velocity (m/s)

Various empirical formulae are available for the evaluation of f, and notable among these is the Colebrook-White equation [19]

$$\frac{1}{\sqrt{f}} = -4\log\left(\frac{k}{1.71d} + \frac{1.26}{Re\sqrt{f}}\right) \quad (2)$$

where k = roughness particle size (which is a measure of the wall surface roughness)

and Re = flow Reynolds Number

Eqn. 2 had been employed in the preparation of a friction factor chart known as the Moody Chart.

The exercise of using either the Moody Chart or Eqn. 2 to determine f and then employing f to determine h_p from Eqn. 1 is found to be somewhat cumbersome for practical design purposes. Thus, the use of pipe flow charts such as Fig. 5 in directly determining losses of pressure head due to pipe friction is more common.

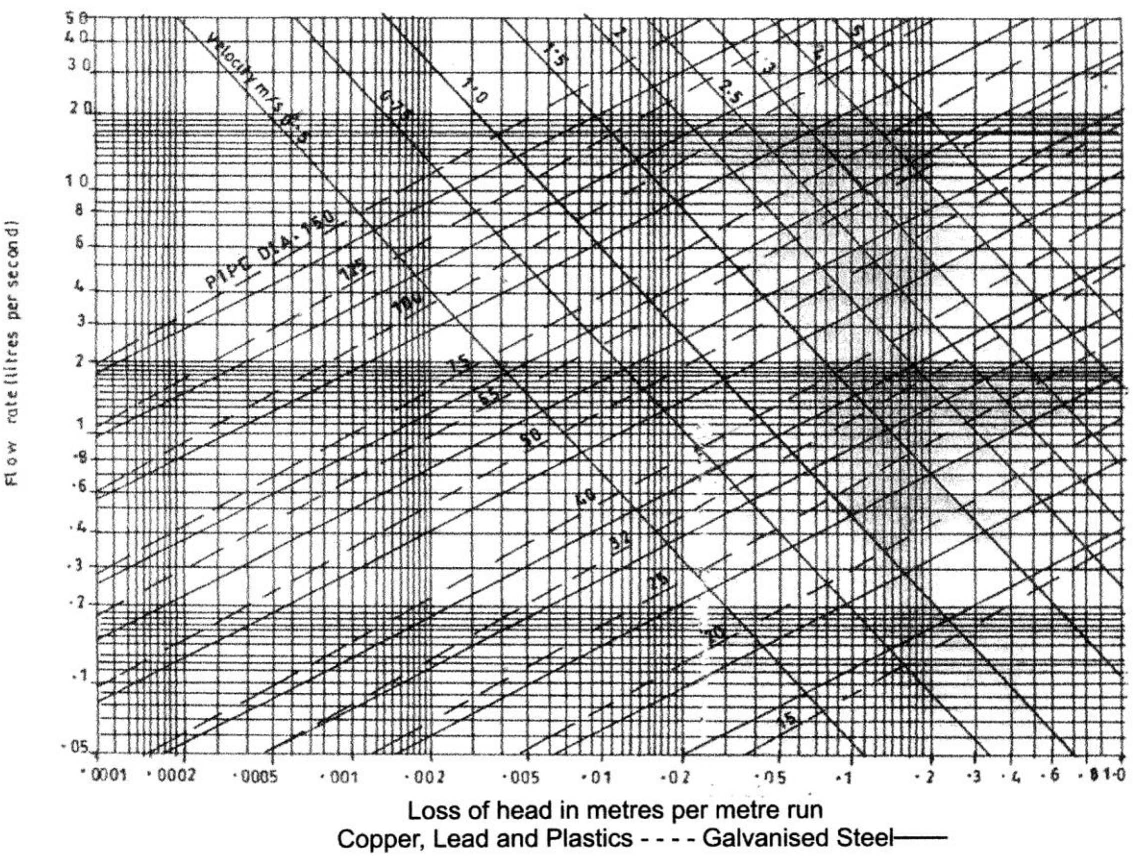


Fig. 5. Pipe Sizing Graph

Another useful expression for evaluating the head loss due to pipe friction is the Hazen – Williams formula expressed in terms of l, d and v as [23]

$$hp = \frac{133.4d^{-0.017}}{C^{1.85}}\left(\frac{l}{d}\right)\frac{v^2}{2g}\left(\frac{1}{vd}\right)^{0.15} \quad (3)$$

where C = Hazen-Williams coefficient

A more directly applicable form of Eqn. 3 [26] is

$$hp = \frac{10.6226}{C^{1.85}}\ d^{-4.867}Q^{1.85} \quad (4)$$

where Q = pump discharge rate (in m^3/s), noting that

$$v = \frac{4Q}{\pi d^2} \quad (5)$$

(d) Pressure losses due to pipe fittings and valves. The head loss h_f through a fitting or valve is usually related to a coefficient K by the equation

$$hf = K\frac{v^2}{2g} \quad (6)$$

(e) Terminal pressure at outlet. This is a measure of the kinetic energy of the fluid at discharge and is given as

$$hd = \frac{v^2}{2g} \tag{7}$$

The sum of the vertical depth, below ground, of the pump and the vertical elevation of the discharge pipe to the reservoir constitutes the total static head which does not vary when the flow rate in the system is varied. All the other components of the total system head vary with velocity, and hence with discharge, as can be inferred from Eqns. 1, 4, 6 and 7. The total system head, therefore, varies with pump discharge.

The selection of a suitable pump requires plotting a curve of total system head for varying flow rates and then superimposing this curve onto the characteristic curves of a set of homologous pumps of a chosen model. The particular pump whose curve cuts the system curve at a flow rate closest to the point of peak efficiency (of the set of pumps) is selected for the duty. This procedure is illustrated in Fig. 6.

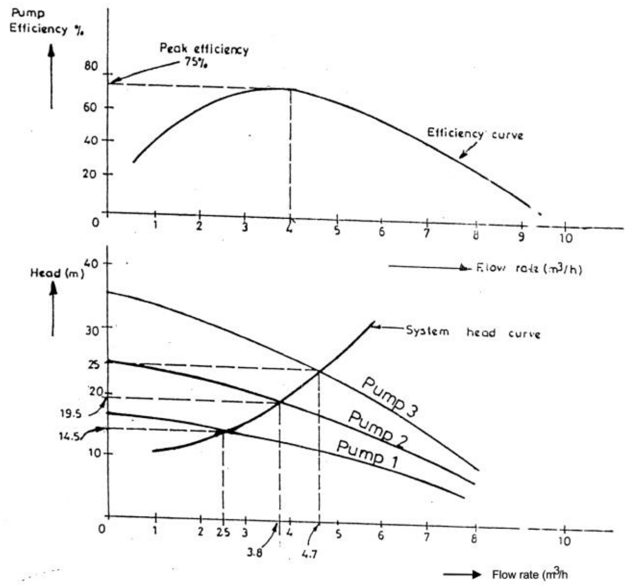


Fig. 6. System Head Curve Superimposed onto Pump Characteristics Curves

In Fig. 6, Pump 2 is selected since the system curve cuts its characteristic curve at 3.8m^3/h, this discharge being the nearest to 4m^3/h at which the peak efficiency occurs.

The point of interception of the curves for the selected pump is the operating point of the system. In the illustration of Fig. 6, this point is thus at 3.8m^3/h discharge and a head of 19.5m

6.2.2. Pump Power Requirement

The power requirement of the pumping system is obtained from the formula [19, 23]

$$P = \frac{\rho g Q H}{\eta} \tag{8}$$

where P = power required by the pump [W]

ρ = density of water [Kg/m^3]

g = acceleration due to gravity, 9.81m/s^2

Q = pump discharge rate [m^3/s]

H = head delivered by the pump [m]

and η = hydraulic efficiency of the pump

Q, H and η are obtained from the pump characteristic curve at the operating point (as in Fig. 6).

6.3. Sizing of the PV Array

The PV array is usually specified in terms of wattage and voltage. It is standard practice to increase the calculated pump power requirement by 25% to compensate for efficiency losses in PV modules [12, 25]. The PV array area, for a system operating during off-sun times, is calculated by the formula [28, 29]

$$PVarea = \frac{E_L}{G_{av} \ x \, \eta_{pv} \ x \ TCF} \tag{9}$$

where E_L = energy required from the PV module daily [kWh/day]

G_{av} = average daily solar energy input [kWh/m^2/day]

η_{pv} = PV energy conversion efficiency

TCF = temperature correction factor

Values of G_{av} are obtained from site solar radiation data. Typical values of η_{pv} provided by some researchers [28, 30] range from 6% to 15% with a theoretical maximum of 20% [31]. Values of TCF corresponding to various PV cell temperatures are also available [29].

For the system operating only during sunhours, and which may not require a battery and inverter, the formula for the PV area is similar to Eqn. 9 but G_{av} would then be replaced by the average energy input for the sunhours.

Furthermore, by standard rating definition, the PV array peak power, at peak solar insolation of 1000W/m^2 is given by [28, 32]

$$\text{PVarraypeakpower} = \text{PVarea x } 1000 \text{ x } \eta_{pv} \tag{10}$$

Thus, with the array peak power obtained, the number of modules of manufacturer's specification at standard test conditions (i.e. 1000W/m^2 and 25°C) can be obtained. The series and parallel configuration of the resulting PV array can then be adjusted according to the required DC bus voltage and current.

6.4. Sizing of the Battery

The storage capacity of the battery is usually calculated according to the relation [27,28,32, 33]

$$Storage\_capacity = \frac{N_c E_L}{24\, DoD.\eta_b.\eta_{inv}} \tag{11}$$

where N_c = highest number of non-sunshine pumping hours in the day over the year.

DoD = maximum permissible depth of discharge of the battery

η_b = battery efficiency

η_{inv} = inverter efficiency

E_L is as defined earlier. N_c is obtained from the sunshine hours history of the site.

The batteries used in solar PV systems are of the deep-discharge type which are designed to provide moderate currents continuously for a long time and may be discharged almost completely without damage [32]. A depth of discharge up to 0.9 is considered safe [32], although a maximum permissible value of 0.8 is usually employed. This value can be regulated by a discharge controller.

Nickel-cadmium and lead-acid batteries are used in PV systems. Nickel-cadmium batteries are quite reliable but are very expensive, so lead-acid batteries are more common. Lead-acid batteries have a usual efficiency of about 0.8 [31]; while a usual inverter efficiency is 0.9 [28].

With the storage capacity determined in watt-hours (Wh), the required ampere-hours (Ah) of the battery is obtained by dividing by the DC bus voltage. The numbers of parallel strings and series connections that form the battery configuration whose total Ah equal the required Ah is determined by the bus voltage and the voltage of the selected single battery.

6.5. Inverter Selection

Inverters are selected using the pump power requirement and it is suggested that 20% to 30% of the actual pump wattage be added to cater for inefficiencies [34].

7. Economic Analysis of PV Pumping Systems

Considering the wide variation of aquifer characteristics in Nigeria, with an associated variation of the cost of groundwater pumping projects , there is a need to first determine the economic viability of solar pumping schemes, vis-à-vis alternate energy sources, before investing resources.

The major economic tool used in analysis of energy systems is the life cycle cost (LCC) analysis. This tool allows for an equal and useful comparison of solar and conventional water pumping technologies. It also allows for comparison of costs among different geographical locations. Using this method, not just the initial cost, but all the future costs (operation and maintenance, replacements, transportation and fuel) can yield a comprehensive and comparative result of total system costs during the life of the system [14, 16, 35 – 40]. Budgetary planning is thus facilitated for financing organizations and communities. From the LCC analysis the payback point of a PV pumping system can also be determined.

The LCC of the PV system includes the sum of all the present worth (PWs) of the costs (including cost of installation) of PV array, pump with controller and accessories, storage batteries, battery charge controller and the inverter; the PWs of the future costs (as listed earlier); as well as the PWs of the cost of the borehole, tank, tank tower, piping and cabling.

To obtain the cost data to be used for the LCC analysis, average prices of such items as PV modules, batteries, charge controllers, and inverters should be obtained. The costs of drilling and development of water wells (i.e. boreholes), construction of tank and tank tower, and the installation of pipes and cables are also to be obtained.

While some of the system components (such as the tank tower) may last indefinitely with proper maintenance, a design lifetime of 25 years is usually taken for the system [27]; except for the pump, with its controller and accessories, which is expected to last 10 years [27] and the battery and inverter which should last 5 years [27, 31]. It is thus anticipated that 2 extra pumps with controller and accessories have to be purchased after 10 years and 20 years; and 4 extra sets of battery and inverter have to be purchased after 5 years, 10 years, 15 years and 20 years, in that succession. The stipulation of these long-term costs take into cognizance the need for proper maintenance of the system components.

The PW of the replacement pumps and batteries which would be purchased in later years are obtained from the equation [28, 36, 37, 41]

$$Cr = C\left(\frac{1+i}{1+d}\right)^n \tag{12}$$

where C_R = present worth of replacement cost

C = present cost

I = inflation rate

d = discount rate

and n = lifetime of item

Utilizing a present operation and maintenance cost (which includes transportation to site, staff emoluments, etc.), of M/year, and the lifetime of the system, the PW of operation and maintenance C_m for future years would be calculated from [28,37]

$$Cm = (M/yr)\,.\left(\frac{1+i}{1+d}\right).\left\{\frac{1-\left(\frac{1+i}{1+d}\right)^n}{1-\left(\frac{1+i}{1+d}\right)}\right\} \tag{13}$$

The LCC is then calculated as the sum of the PWs.

It is sometimes useful to calculate the LCC of a system on an annual basis. The annualized LCC (i.e. ALCC) of the PV pumping system in terms of present day money can be calculated as [28,36, 37]

$$ALCC = LCC\left\{\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{n}}\right\} \tag{14}$$

The foregoing economic analysis carried out for different localities would provide the cost per unit of solar energy for groundwater pumping, this information being useful in budgeting and project planning.

For cost comparision with other borehole water pumping methods, such as the use of diesel generator pumps, LCC for these other methods need to be carried for equivalent system parameters.

8. Conclusion

Considering the abundance of water and solar energy in Nigeria, groundwater pumping using the photovoltaic system appears to be a viable means of providing water for the Nigerian populace, especially in localities where the national electricity grid is not yet connected. The methods outlined in this paper for groundwater pumping system design and economic analysis can be applied.

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