International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 12 Dec. 2022, pp: 848-857 www.ijaem.net ISSN: 2395-5252

Simulation of photovoltaic (PV) power needs of solar drinking water pumping system of household communities

Amatobi, D. A.[1], Adenaike, O. A.[2], Okeke, E. C.[3] and Okon, S. S.[4]
[1, 2,3, 4] Department of Civil Engineering Technology, Akanu Ibiam Federal Polytechnic Unwana, Nigeria

---

Submitted: 18-12-2022 Accepted: 31-12-2022

ABSTRACT
The awareness of solar PV powered boreholes is increasing in the developing countries. This unfortunately is resulting in unprofessional designs and installations of the solar water PV system, leading to high rate of failures. The availability of a basic design that is simple enough can assist technicians lacking adequate theoretical capacity to do proper designs and installations that will meet requirements. This study determined the prevailing physical parameters regarding PV solar water pumping system at Ohaisu Ward 2 community in Afikpo North Local Government Area of Ebonyi State, Nigeria. This study set forth simplified design equations for determination of energy requirements for a solar PV water pumping system. Using 10,000 Monte Carlo simulations, the study determined the range of key parameters for pump power requirements and photovoltaic power needs based on the prevailing physical conditions of a household community of 700 people. The study can aid elimination or at least reduction of rigorous design computations without significant losses in efficiency or optimization of solar water pumping projects in specific drinking water communities of developing countries.

KEYWORDS: Photovoltaic, water pump, borehole, drinking water, household

I. INTRODUCTION

A right to clean drinking water is a right to life (United Nations, 2010), but 2 billion people across the world still lack access to safely managed drinking water at their homes (CDC, 2022). About 829,000 people, many of whom are children under 5, lose their lives annually due to diarrhea largely linked to unsafe water, sanitation and hygiene (WHO, 2022). Unavailability of clean water reduces hand washing and good sanitation practices (Aregu, et. al, 2021). Therefore, any technology that brings clean water to people should be sustained, for it is a technology for life.

The photovoltaic (PV) technology for generation of electricity has advanced over the past decades. An important aspect of this advancement is the production of solar electric pumps for lifting water. The development of variable frequency inverters has widened the scope of PV modules in pump applications, making it possible for the PV system to power all types of electric pumps. Many people with the poorest access to clean water also lack access to grid-electricity, but most of them live in regions endowed with ample sunshine. Hence, the application of solar water pumping system for harnessing clean ground water is a technology that has a great potential of drastically reducing the clean water access gaps across the world.

Fortunately, the cost of using solar PV system to pump water from boreholes has fallen dramatically in recent years. Robust and reliable solar pumping equipment are fast emerging with the cost of solar PV modules reducing by 85% over the past decade (NREL, 2021). Many solar water intervention projects are being implemented in the developing countries by government agencies, donour agencies, non-governmental organizations and other stakeholders. This is in spirited efforts to bring clean water to the people, and hence to minimize the adverse health and socio-economic consequences of poor water access currently being experienced by millions across the globe. However, sustainability requires that the solar water technology pumping system be professionally designed, implemented and properly managed.

The awareness of solar PV powered boreholes is increasing in Nigeria. This unfortunately is resulting in unprofessional designs and installations of the solar water PV system. In Nigeria, high rate of failure of solar water pump projects has been reported (Rilwanu, 2016; Agabi

& Nyoko, 2021). Riwanu found that about 58% solar water boreholes commissioned in Kumbotso Local Government Area Kano state, Nigeria were not functional. The causes of failure of solar water system include poor design, poor implementation, lack of maintenance, stealing of components, inadequate security, and exclusion of key stakeholders and their needs, especially the user communities, in the system design and implementation (Anoliefo et. al 2020). A proper design will reduce the chances of the other forms of failure. A good design meets consumers' demand, and ensures that the system runs efficiently.

A proper design involves the correct estimation of water demand and energy requirements, and determination of photovoltaic module requirements. When it comes to technical systems in the developing countries, expertise or professional practice is usually at a very low level. In Nigeria, for instance most technical jobs are left in the hands of uncertified technicians most of whom lack the theoretical rudiments of the job they do.

In the case of solar water pumping system, availability of basic design that is simple enough can assist technicians lacking adequate theoretical capacity to apply proper design methodologies and carry out installations that meet requirements. Such design will also save time for professionals involved in solar water pump system.

Basically a proper design of the photovoltaic water pumping systems consists of calculating the photovoltaic power needs and determining from the power needs the PV Pump, PV modules, controllers and other electrical components (including batteries and inverters where applicable).

Some basic solar water pump system designs are available in literature. However, these studies have not adequately considered the capacities of those who are actually involved in the implementation of the system on the field. This study attempts to simulate the photovoltaic power needs of specific population of user community, given the ranges of the observed average daily horizontal incident solar irradiance, daily water demand, and total dynamic heads for boreholes within the community. The objective of the study includes the following:

1. Determine the range of daily water demand of the study area
2. Estimate the range of total dynamic head from existing boreholes in the study area
3. Establish the range of the daily average horizontal irradiation in the study area
4. Formulate the equations for determination of the photovoltaic power needs
5. Perform 10,000 Monte Carlo situations and carry out sensitivity analyses to obtain photovoltaic power needs scenario, based on the formulated equations

II. MATERIALS AND METHODS

2.1 The context of the study area

The study area, Ohaisu Ward 2, is an electoral ward in Afikpo North Local Government Area of Ebonyi State, Nigeria. Afikpo North Local Government Area is situated at 5.9054° N, 7.9375° E. The local government area has 13 electoral wards and has a population of about 157,000 people by the last Nigerian census of 2006 (National Bureau of Statistics, 2013). Using the Ebonyi Sate growth rate of about 2.7% (USAID & Health Plus, 2017), the local government area currently has approximately 240,000 people. Going by the average electoral ward population, Ohaisu Ward 2 has a population of about 18,500 people.

Ohaisu Ward 2 was chosen to represent electoral ward levels of household communities with gaps in clean water access in Nigeria. Seventy million Nigerians (33% of the population) had no access to clean water in 2021 (Editorial, 2022). The household settlement in Ohaisu Ward 2 is in clusters, called Ezi (compound). The study area has no municipal water supplies, and water supply largely remains a private arrangement of each household or community. Sources of drinking water in the area include surface water, rainwater, spring water, packaged water (called pure water), bottled water and the water wells and boreholes. The water borehole is currently the most popular source of drinking water in the study area. Majority of the water boreholes are powered by the hand and the motorized pumps. The solar powered boreholes are creeping in, even though some are already failing. Hence, the study area is seen as a good beneficiary of this study and its methods.

2.2 Data collection

The study collected data from surveys of the study area and from a review of facts in literature. Instruments used in the survey include structured questionnaire, oral face-face interviews and site visits. Daily drinking water demand data were obtained from 96 respondents, 10 existing boreholes (with overhead water tanks) sites were visited and the range of total dynamic head was obtained from information gathered from borehole owners. The average horizontal solar irradiance for the study area was obtained from literature. Other factors obtained from literature include frictional factors for pipes and loss coefficients of fittings.

2.3 Determination of the total dynamic head (TDH)

As explained in section 2.2 the piping details of 10 existing water boreholes were obtained through site visit. Through the surveys, the TDH of each of the boreholes was calculated and a range of values (minimum, maximum, mean and standard deviation) of TDH (m) was obtained for the study area. TDH [m] is the total head the pump has to overcome. The TDH is the algebraic sum of the static head $\mathbf{H_S}$, the frictional head loss $\mathbf{H_F}$ and the residual loss $\mathbf{H_R}$.
Hence TDH can be gives as equation 1:

$$\mathrm{TDH} = \mathrm{H_S} + \mathrm{H_F} + \mathrm{H_R} \qquad (1)$$

The static head, $\mathbf{H_S}$ **[m]**, is the vertical height from pump suction to the inlet of the storage tank. The friction head loss, $\mathbf{H_F}$ [m] was obtained from Darcy-Weisibatch equation for head loss in circular pipes, using equation 2:

$$\mathrm{H_F} = \frac{4\mathrm{fL}}{\mathrm{D}} \times \frac{\mathrm{v}^2}{2\mathrm{g}} \qquad (2)$$

Where $\mathbf{H_F}$ [m] is the frictional head loss head, **f** is the friction factor; L[m] is the length of pipe, **D** [m] is the pipe diameter. **v** [m/s] is the velocity of flow and **g**[m/s^2] is the acceleration due to gravity.
The frictional factors for circular pipes were obtained from the Moody diagram (McGovern, 2011). The velocity of flows was calculated from equation 3:

$$\mathrm{v} = \frac{\mathrm{Q}}{\mathrm{A}} \qquad (3)$$

Where **Q** [m^3/s] is the volume flow rate of water and **A [m^2]** is the cross-sectional area of the pipe internal surface.
Frictional head loses at the fittings were obtained using equation 4. From Darcy-Wesibatch equation, the frictional head loss at circular pipe fitting can be written as:

$$\mathrm{h_l} = 4\mathrm{fl_e}\,\mathrm{v}^2/\mathrm{d}\;2\mathrm{g} \;=\; \mathrm{K}\,\mathrm{v}^2/2\mathrm{g} \qquad (4)$$

Where $\mathbf{h_l}$ [m] is the frictional head loss at the fittings, $\mathbf{l_e}$ [m] is the equivalent length of pipe, of diameter, **d [m],** that would produce a friction head loss equivalent to the specific pipe fitting.

Hence:

$$\mathrm{l_e} = \mathrm{Kd}/4\mathrm{f} \qquad (5)$$

Where K is the fitting loss coefficient. The K values were obtained from table 1.

Table 1. Fitting loss coefficient, K

Fitting	**Minor Loss Coefficient K**
Tee, Flanged, Dividing Line Flow	0.2
Tee, Threaded, Dividing Line Flow	0.9
Tee, Flanged, Dividing Branched Flow	1.0
Tee, Threaded , Dividing Branch Flow	2.0
Union, Threaded	0.08
Elbow, Flanged Regular 90°	0.3
Elbow, Threaded Regular 90°	1.5
Elbow, Threaded Regular 45°	0.4
Elbow, Flanged Long Radius 90°	0.2
Elbow, Threaded Long Radius 90°	0.7
Elbow, Flanged Long Radius 45°	0.2
Return Bend, Flanged 180°	0.2
Return Bend, Threaded 180°	1.5
Globe Valve, Fully Open	10

Fitting	Minor Loss Coefficient K
Angle Valve, Fully Open	2
Gate Valve, Fully Open	0.15
Gate Valve, 1/4 Closed	0.26
Gate Valve, 1/2 Closed	2.1
Gate Valve, 3/4 Closed	17
Swing Check Valve, Forward Flow	2
Ball Valve, Fully Open	0.05
Ball Valve, 1/3 Closed	5.5
Ball Valve, 2/3 Closed	200
Diaphragm Valve, Open	2.3
Diaphragm Valve, Half Open	4.3
Diaphragm Valve, 1/4 Open	21
Water meter	7

Source: Engineering ToolBox, (2004)

With the equivalent length of fitting obtained, the Darcy-Weisibatch equation for head loss in circular pipes can be rewritten as equation 6:

$$H_L = \frac{4f(L+l_e)}{D} \times \frac{V^2}{2g} \qquad (6)$$

The Residual head loss H_R is the additional pressure the fluid encounters at the delivery point. For pumping to tank, it ranges between 0 m and 10 m. For this study, H_R was taken as 5m, since the delivery point was considered relatively simple.

Fig, 1 is a representation of the basic solar water pumping system configuration for determination of TDH.

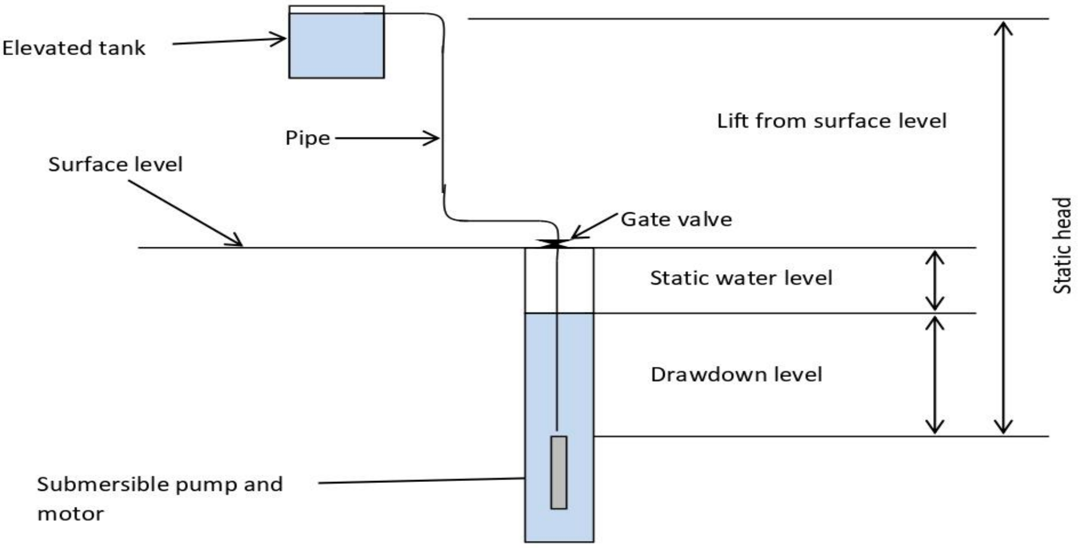

Figure 1. Basic solar water pumping system configuration

2.4 Equations for determination of the photovoltaic power (PPV) needs

2.4.1 Determination of the design pump flow rate (Q)

The pump flow rate Q [m^3/s] was determined as the amount of water delivered by the pump per second to meet the daily drinking water demand of a given population within the peak sunshine hours. The pump flow rate was obtained using equation 7

$$Q = \frac{W_D}{3600 \times H_S} \qquad (7)$$

Where **Q** [m^3/s] is the pump flow rate, $\mathbf{W_D}$ **[m^3/day]** is the daily drinking water demand and $\mathbf{H_S}$ **[hr]** is the peak sunshine hours. The peak sunshine hours range between 4.7 hours and 9.8 hours in the study area (Weather Atlas, 2022). This study assumed six hours for design purpose.

2.4.2 Determination of hydraulic power

The hydraulic power, P_H [W] is the power required to supply water at the design flow rate, Q [m^3/s] and the TDH [m]. The hydraulic power is given by equation 8:

$$P_H = Q \times TDH \times \rho \times g$$

(8)

where: **ρ** is the water density [1000 kg/m^3 at 0˚C and 1 bar], **g** is the acceleration due to gravity [9.81 m/s^2].

2.4.3 Determination of electric power

The electric power input to the motor-pump unit, P_{El} [W], is given by equation 9:

$$P_{El} = \frac{P_H}{\eta_{MP}} \qquad (9)$$

Where η_{MP} is the efficiency of the submersible pump motor unit. The pump efficiency used in this study is 25% (Hague et al., 2019).

2.4.4 Average horizontal solar radiation of the study area

The average horizontal solar irradiance of the study area was obtained from table 2.

Table 2. Average horizontal solar irradiance for Afikpo, Nigeria

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Irradiance (kW/m^2)	5.0	4.8	4.3	4.2	3.9	3.9	4.0	4.2	3.9	3.6	4.2	4.8

Source: Weatherspark.com (2022).

2.4.5 Determination of the photovoltaic power needs

The power output of the photovoltaic panel was determined using equation 10:

$$P_{PV} = \frac{P_{EI} \times G_{REF}}{G_{GLOB} \times F_Q} \qquad (10)$$

where: P_{PV} is the peak power of the PV array under standard test conditions (STC): (Irradiance = 1000 W/m^2; AM 1.5, cell temperature = 25˚C) [W_p]; $\mathbf{G_{GLOB}}$ is the average global solar radiance on a horizontal surface [kW/m^2] per day; G_{REF} is the incident solar irradiance at STC [1 kW/m^2]; and $\mathbf{F_Q}$ is the quality factor of the PV array system.

For this study, the global solar radiance on a horizontal surface [kW/m^2] per day was obtained from table 2. The quality factor was taken as 0.85 (Takyi , 2021).

2.5 Solar water pump system configuration

The basic system configuration of the solar water pump adopted by this study is as shown in Fig.2 .

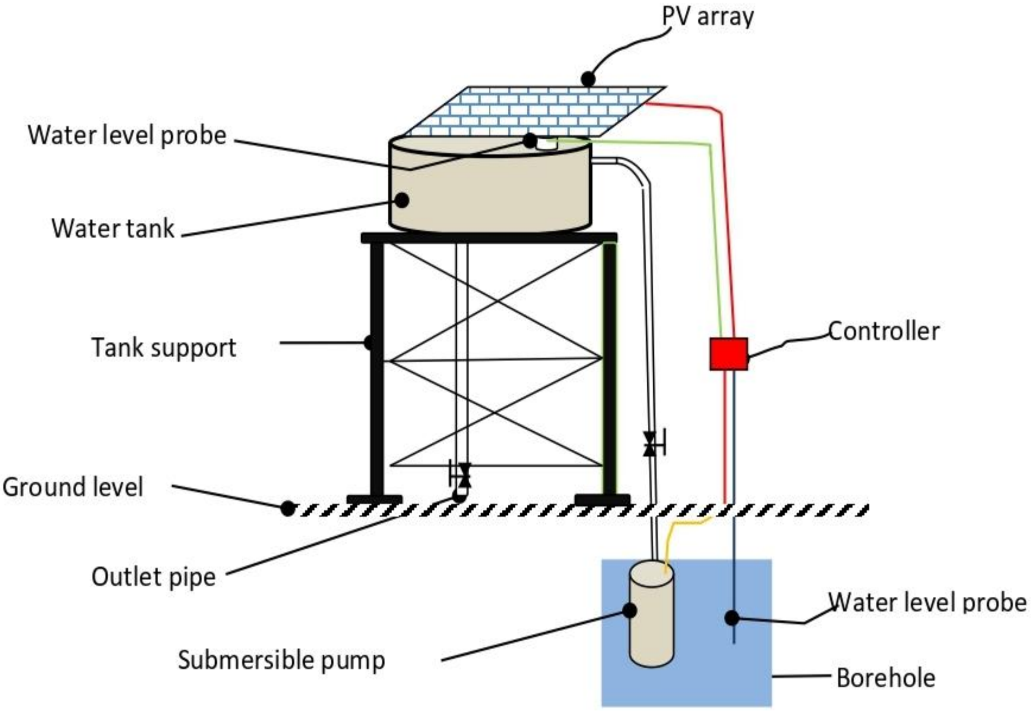

Figure 2. Basic configuration of the solar water pump PV system

III. RESULTS AND DISCUSSION

3.1 Input data used in the simulation

Table 3 shows some data obtained during the study and were used in the simulation. Most of the data are field dependent. They reflect the actual situation in the study area. The water demand was based on the household community population of 700 people. The mean water demand per person per day of 24.34 litres is close to the suggested threshold of 20 litres per person per day (World Water Week, 2021), but the range and the high standard deviation suggest that many people in the study area do not meet the minimum requirement. The values of per capital water consumption were within the range obtained by some Nigerian authors (Nnaji et al., 2013). This result affirms that access to clean drinking water is generally low in Nigeria.

The peak sunshine hours in the study area ranges between 4.7 and 9.8 hours, and the horizontal solar incidence of over 3.6 KW/m^2 indicate that the study area is favourable for solar energy harnessing, including the solar water pumping system. The total dynamic head for water boreholes in the study area ranges between 18m and 45m. This is because the study area lies in low altitude, close to the sea level, and hence the water table is not far from the surface. This situation is also favourable for ground water extraction. The challenge lies in obtaining the relevant data and using them for proper design of solar energy applications. The current study is an attempt to address this challenge.

Table 3. Input data obtained in respect of the study area

Description	**constant value**	**Min**	**Max**	**Mean**	**std deviation**	**Remarks**
Water demand (L/per person per day)	…..	7.5	45	24.34	11.02	From field survey
Water demand (m^3/per person per day	……	0.0075	0.045	0.02434	0.01102	From Calculation
Population of users -700	700					Household cluster size
Daily water demand (m^3)/day	……..	5.25	31.5	17.038	7.714	From Calculation
Peak sunshine (hours/day)	6					Within the lower range
Pump flow rate , Q (m^3/s)	……	0.00024	0.00146	0.00079	0.00036	From Calculation
Total Dynamic head (TDH) (m)	………..	18	45	31.5	6.75	From Field Survey
Submersible pump efficiency	0.25					
Global hor. Irradiance (kW/m^2)	………	3.6	5	4.23	0.43	Weatherspark (2022).
Incident solar radiance at STC (kW/m2)	1					Weatherspark (2022).
Quality factor	0.85					Takyi (2021)
Density of water (kg/m^3)	1000					
Acceleration due to gravity (m/s^2)	9.81					

3.2 Simulation of photovoltaic power requirements for the study area

Table 4 shows the summary of results obtained using 10,000 Monte Carlo simulations of input data into the solar pump PV system equations. From table 4, the statistics of the possible values of parameters together with the required photovoltaic power needs are displayed. The statistics include the minimum, maximum, mean, standard deviation, mode and median values. The photovoltaic power needs to meet the range of daily water demands for a population of 700 people in the study area were between 41.10 Wp and 830.73Wp.

Table 4. Simulation summary of pump-system parameters in the study area

Description	**Min**	**Max**	**Mean**	**Std Dev**	**mode**	**median**
Daily water demand (m^3/day)	5.25	31.50	17.15	7.05	5.25	17.07
Pump flow rate (m^3/s)	0.00024	0.00146	0.00079	0.00033	0.00024	0.00079
Total dynamic head (m)	18.00	45.00	31.48	6.48	45.00	31.54
Hydraulic power (W)	42.92	643.78	245.63	114.95	42.92	234.81
Electric power (W)	171.68	2575.13	982.52	459.80	171.68	939.23
Irradiance(kW/m^2)	3.60	5.00	4.24	0.39	3.60	4.23
Photovoltaic power (Wp)	41.10	830.73	274.99	131.85	40.39	261.63

Figs. 3--5 show the distribution of key parameters (daily water demand, total dynamic head and photovoltaic power needs, respectively) based on 10,000 Monte Carlo simulation. From the curves, optimal parameters for the determination of PPV power and PV array needs can be inferred for the study area without necessarily carrying out rigorous computations. Where such computations are feasible, the values obtained in this study can act as guide.

It is advisable to use the mean and median for calculation of the PV module requirements.

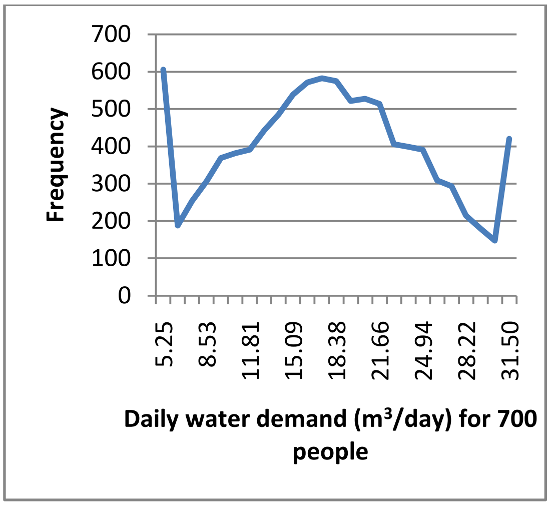

Figure 3. Distribution of daily water demand based on 10,000 Monte Carlo simulations

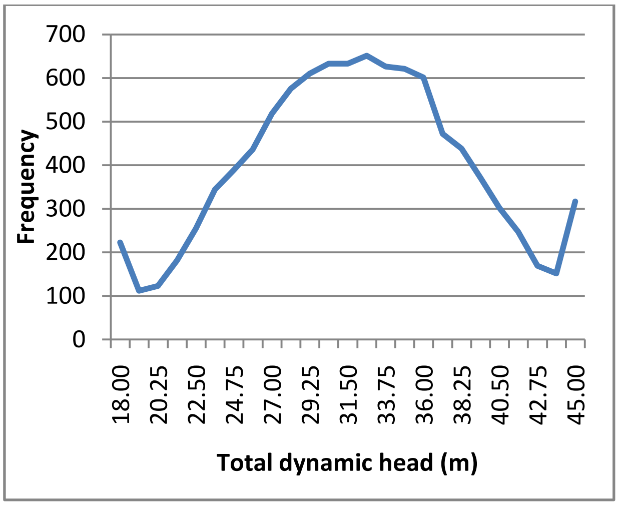

Figure 4. Distribution of total dynamic head based on 10,000 Monte Carlo simulations

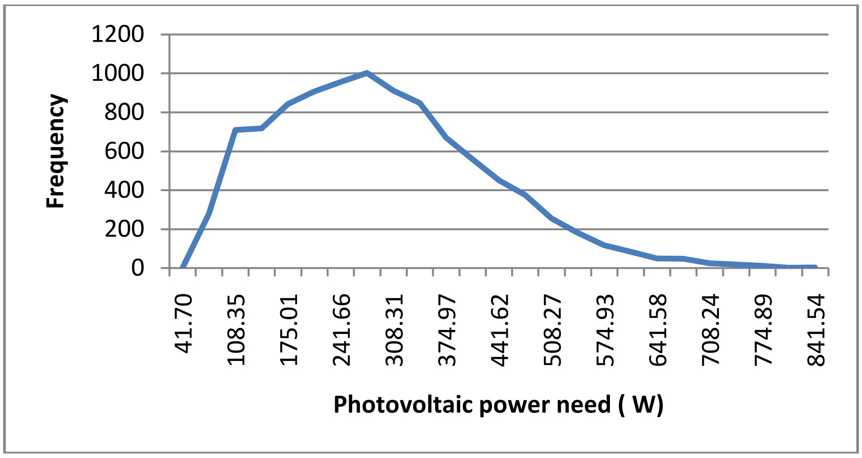

Figure 5. Distribution of photovoltaic power need based on 10,000 Monte Carlo simulations

IV. CONCLUSION

This study set forth simplified design equations for determination of energy requirements for a solar PV water pumping system. The study determined the range of key parameters for pump power requirements and photovoltaic power needs, based on the prevailing physical conditions of a household community. The parameters are required for calculation and selection of PV arrays for proper design of the solar PV pumping systems to meet the daily water demand of 700 people in the current study area. The range of parameters obtained, using 10,000 Monte Carlo simulations, include the daily water demand, the total dynamic head, the daily average horizontal irradiance, and the photovoltaic power needs.

The prevailing physical conditions in the study area were assumed to be accommodated within the range of values obtained. Hence, the study believes that the mean and median values obtained can be applied to determine the pump and solar PV requirements to meet the daily drinking water demand of the study area. This study can aid elimination or at least reduction of rigorous design computations without significant losses in efficiency or optimization of solar PV water pumping projects in specific drinking water communities.

REFERENCES

[1]. Agabi, I. J. & Nyoko, A .P. (2021). Design procedures for standalone photovoltaic solar water pumping system for rural communities. International Journal of Scientific Engineering and Science 5, (6), 13-19.

[2]. Anoliefo , E., Oparaku, O. U., Egoigwe, S. & Olisa, S.(2020). Determination of the failure mechanism of standalone solar street light. Nigerian Journal of Technology (NIJOTECH) 39 (. 2), 572 – 578. http://dx.doi.org/10.4314/njt.v39i1.28

[3]. Aregu,M. B., Kanno, G. G., Ashuro, Z., Alembo, A. & Alemayehu. A. (2021). Safe water supply challenges for hand hygiene in the prevention of COVID-19 in Southern Nations, Nationalities, and People's Region (SNNPR), Ethiopia. Heliyon, 7(11). https://doi.org/10.1016/j.heliyon.2021.e08430.

[4]. CDC. (2022) . Global WASH Fast Facts. Centers for disease control and prevention, national center. https://www.cdc.gov/healthywater/global/wash_statistics.html.

[5]. Editorial. (2022). Nigerians deserve potable water. Daily Trust. Online. 02 December, 2022. https://dailytrust.com/nigerians-deserve-potable-water/

[6]. Engineering ToolBox, (2004). Pipe and Tube System Components - Minor (Dynamic) Loss Coefficients. [online] https://www.engineeringtoolbox.com/minor-loss-coefficients-pipes-d_626.html

[7]. Hague, M .F., Islam, M. S., Islam, M. R., Hanju, H. & Akhter, M .S,(2019). Energy efficiency improvement of submersible pumps using in barind area of Bangladesh. Energy Procedia, 160, 123–130.

[8]. National Bureau of Statistics. (2013). Annual abstract of statistics, 2011. http://istmat.info/files/uploads/53129/annual_abstract_of_statistics_2011.pdf

[9]. Nnaji, C .C, Eluwa, C., Nwoji. C, (2013). Dynamics of domestic water supply and consumption in a semi-urban Nigerian city. Habitat International 40 , 127e135. http://dx.doi.org/10.1016/j.habitatint.2013.03.007

[10]. NREL.(2021). Documenting a decade of cost declines for PV systems. The National Renewable Energy Laboratory. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html

[11]. McGovern, J. (2011). Technical note: Friction diagrams for pipe flow. Dublin Institute of Technology. https://www.researchgate.net/publication/254584636_Technical_Note_Friction_Factor_Diagrams_for_Pipe_Flow

[12]. Rilwanu, Y. K. (2016). Performance and failure of solar boreholes for water supply in Kumbotso Local Government Area Kano State, Nigeria. Dutse Journal of Pure and Applied Sciences (DUJOPAS) 2(2).

[13]. Takyi, G. (2021). Performance characterization of polycrystalline silicon photovoltaic modules installed in Kumasi, Ghana. Nigerian Journal of Technology, 40,(3), 461–471. DOI: 10.4314/njt.v40i3.12.

[14]. The United Nations. (2010). The human right to water and sanitation. Resolution adopted by the General Assembly on 28 July 2010. https://documents-dds-ny.un.org/doc/UNDOC/GEN/N09/479/35/PDF/N0947935.pdf?OpenElement

[15]. USAID and Health Plus. (2017). Nigeria population and development Ebonyi State factsheet. http://www.healthpolicyplus.com/ns/pubs/7149-7286_ebonyirapidfactsheet.pdf

[16]. Weather Atlas. (2022). Climate and monthly weather forecast Afikpo, Nigeria. https://www.weather-atlas.com/en/nigeria/afikpo-climate#daylight_sunshine

[17]. Weather Spark. (2022). Climate and Average Weather Year Round in Afikpo Nigeria. https://weatherspark.com/y/55023/Average-Weather-in-Afikpo-Nigeria-Year-Round

[18]. WHO. (2022). Drinking-water: Key facts. World health Organization. https://www.who.int/news-room/fact-sheets/detail/drinking-water

[19]. World Water Week. (2021). 20 litres per person per day – interactive. https://www.worldwaterweek.org/event/9590-20-litres-per-person-per-day---interactive