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Original Research Paper

Design of a Solar Powered Water Supply System for Kagadi Model Primary School in Uganda

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Abstract: Adequate supply of clean water is even more significant for a primary school as it ensures hydration, sanitation, hygiene leading to a general wellbeing of the pupils. This research work successful designed a solar powered water supply system for Kagadi Model Primary School (KMPS) and its environs. The research design takes into account the population of 1725 students with total daily water demand of 31.05m3/day and mean solar radiation of 5.1kwh which corresponds to an elevation /slope of 1degree. The flow rate of 6.2105m3/day/hour was obtained using 5.1kwh irradiance. The developed system will help to distribute water fairly to the KMPS and its environ at very a cheap and steady manner for the pump will be powered with solar energy of 200Wp. The solar water pump of 211.407W was energized using solar energy system to pump water into the storage facility (reservoir) before distributing it by the help of gravitational force to various locations for consumption. The cost of running this designed solar powered pump for the period of 20years will generate a net income of 2.28billion Ugandan shilling compared to conventional way they are running it as of 2023. This solar powered water system when implemented will curb the problem of water scarcity, provide clean water and reduce unhygienic nature of the environment, boast Uganda economy as it in line with Sustainable Development Goals (SDGs). This study recommends the implementation of this design to provide, cheap, clean and steady water supply for the residents of the study area.

Keywords: KMPS, Photovoltaic, SDGs, Solar Water Pump.

1. Introduction

Urbanization, migration and rapid increase in Ugandan population have drastically increased the demand for clean and safe water in Uganda according to the Ugandan Ministry of Water and Environment. A source of energy to pump water is also a notable problem in developing countries like Uganda. The cost of running diesel to meetup with the water demand of 48,582,334 population of Uganda as of 2023 will be so expensive and exorbitant to spend. The use of renewable energy sources as an alternative method of steady water supply at low cost in developing countries should be their utmost desire. This can also be encouraged because the cost of purchasing and installing of renewable energy systems such as photovoltaic (PV) pumps is cheaper, user friendly, easy to maintain than other conventional energy sources of water pump [1]. Solar Photovoltaic (PV) sources of renewable energy has been identified and adopted as one of the fastest renewable energy that will dominate in terms of energy generation in the future. This is because of its clean, free gift in nature, ease of maintenance and user friendly [2]–[14]. These economic and health importance made PV energy sources attractive for many applications, especially in rural and remote areas of most of the developing countries like Uganda. Solar photovoltaic (PV) water pumping systems have been recommended as an alternative/suitable sources of energy supply for areas with inadequate electricity in poor countries with a high solar irradiance. Solar photovoltaic water pumping systems can provide water for domestic and farming purposes without the need for any kind of fuel or the extensive maintenance required by diesel pumps. They are easy to install and operate, highly reliable, durable and user friendly, produces clean and safe energy which can be installed at the site of use as standalone or building integrated rendering long pipelines unnecessary [15]. The output of solar power system varies throughout the day with respect to changes in weather conditions or partial shading of the panel. A properly and a well-designed solar pumping system will be efficient, simple and reliable and has the ability to work effectively for a very long time without maintenance. Solar powered pumping systems serves many purposes such as Town-city water supply, livestock watering, irrigation and so on. The use of solar pump will as well help in steady water supply in Ugandan schools which will in indirectly curb high record of fire disasters amongst schools in Uganda [16], [17]. The Ugandan government is currently implementing a solar PV electrification of schools and other institutions in selected districts which are remote from the national grid as part of a national strategy to enhance the contribution of renewable sources of energy to the overall energy supply.

2. Literature Review

The cost feasibility study of per capital cost, operating cost, maintenance cost and performance of renewable sources of energy (solar Pump) and none renewable sources (diesel pump) as a means of water supply powering source.

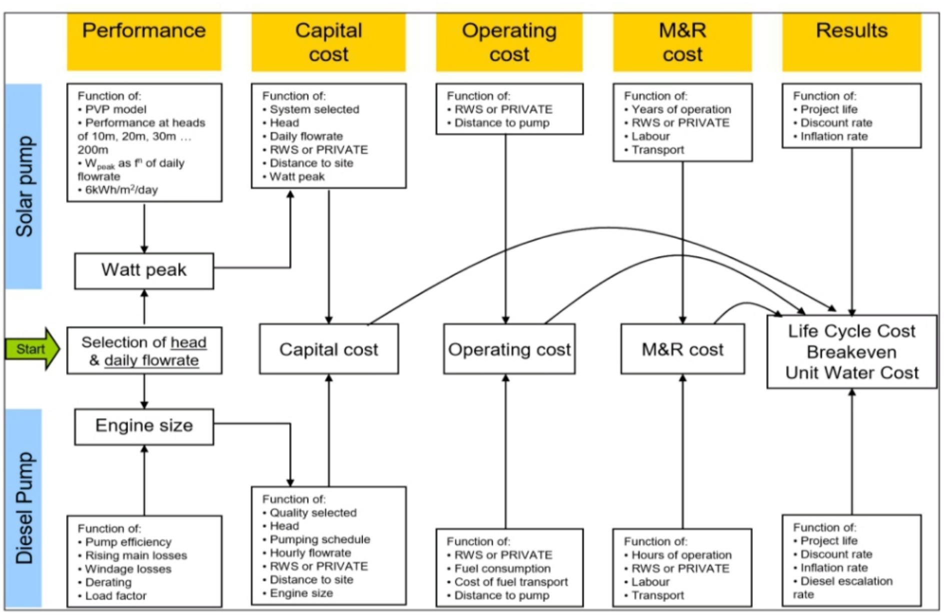

Figure 1. Feasibility Analysis of Solar Pump and Diesel Pump

The summary in Figure 1 showered that renewable sources of pumping water is the best sources of pumping water because of its cheap, low maintenance cost, clean and safe sources of energy, durability and high performance.

Figure 2. Rainfall Profile of Uganda [18]

The topography within 2 miles of Kagadi contains significant variations in elevation, with a maximum elevation change of 722 feet and an average elevation above sea level of 3,995 feet. From figure 2, it was observed that November experiences the highest rainfall (77%) in Uganda and as a result of that there will be less demand for water between September to November in Uganda due to natural rainfall which can easily be harvested.

In 2009 about 150 public institutions in Uganda were powered with 360 kW of PV electricity whereas the total capacity of the overall solar PV installations in rural areas of Uganda amounts to 6 MW. Despite this success, the percentage contribution of solar energy to the total energy mix is insignificant (less than 1%). Studies sponsored by Ministry of Energy have shown that Uganda holds tremendous potential in solar energy but only a small potion has been tapped [14], [19], [20].

Figure 3. Location of the Area on Map of Uganda

Figure 3 is the map of Kagadi Model Primary School located in Kagadi District, Kagadi Town Council near Kagadi District Headquarters, along Kyenjojo – Hoima Road, Uganda. It is approximately 95 kilometres south west of Hoima and 245 kilometres west of Kampala. The coordinates of the area are 0056’28.0” N, 30048’29.0” E (Latitude: 0.941111; Longitude: 30.810833).

The main problem pupils and staff of Kagadi Model Primary School (KMPS) are facing is inadequate water supply as result of long distance to the nearer water source and inconsistent rainfall in the region. The school continuously incur the daily costs of purchasing water and intervening human labour which affects the planned budget for the school leading to poor academic performance. Therefore, a unique phenomenon to acquire a continuous supply of safe and clean water in the school should be paramount for the healthiness of the students, staff and the community at large. Renewable forms of energy such as solar and wind can be used in providing steady, safe and clean water in the area as they are abundantly available in nature. Solar and wind can be harnessed and converted into mechanical energy for pumping water to a reservoir which has the capacity of distributing water to all the areas of the school. This can be achieved by designing a solar powered water supply system in the school that will have the capacity of automatically suppling steady water to the reservoir. Solar powered water pumping systems can provide drinking water without the need for any kind of fuel or the extensive maintenance required by diesel pumps. This drawback of the school can be solved by using the abundant, costless available natural resources (solar) in the country for the wellbeing of the school and nearby community.

3. Methodology

3.1. Geometer

A global positioning system (GPS) receiver was used to obtain the spatial attributes of the eleveation of Kagadi Model Primary School located in Kagadi District above sea level. The Coordinates waypoints was taken at an interval of 50metres along the border of Kagadi Model Primary School for the purpose of mapping it on the GIS platform.

3.2. Pyranometers

This devices was used to measure the climatic conditions of Kagadi Model Primary School in Uganda with respect to the daily sun irradiance. The physically obtained data was still compared with insolation potential data of the Uganda Meteorological Department. Table 1 is the climatic condition statistical data.

Table 1. Summary of the Obtained Data

Elevations	Yes	No
Is your site accessible?	✓	
Is your site highly populated?	✓	
Is there a reliable source of water?	✓	
Is the mean solar irradiation of your site 4.5kwh/m2	✓	
Is your site located in a conservation area or in an area of natural beauty (aonb)		✓
Is the distance between your chosen solar system installation point and the nearest obstacle more than twice your proposed grid height?	✓	
Do you intend to mount your solar system to a roof of a dwelling?		✓

3.3. Method Used

3.3.1. Tilt Angle

Various angles representing typical roof pitches were compared to that of the latitude angle (the optimum angle) to determine if using a typical roof slope would make any difference in the effectiveness of the solar water pumping system [12]. Kagadi Town Council coordinates are 0.9354°S and 30.8086°E with an elevation of 1,250 m. Based on the kagadi location the ideal array tilt would be 0.9354 degrees and face north at zero degrees. A PV-Watts analysis was conducted to determine approximate solar insolation. Data collected was for fixed tilt panels using single tracking systems of

Kagadi town and its environs. Therefore, Table 2 shows solar radiation data for the Kagadi town for an array at latitude as compared to one at various roof pitches.

Table 2. Data for Fixed Panels at Various Roof-Pitches in Kagadi Town Council

Elevation/Slope (Degrees)	Array Type	Direction	Solar radiation (kwh/m^2/day)
8/12	Fixed	North (0)	6.3
9/12	Fixed	North (0)	6.0
10/12	Fixed	North (0)	5.7
11/12	Fixed	North (0)	5.4
12/12	Fixed	North (0)	5.1
13/12	Fixed	North (0)	4.8
14/12	Fixed	North (0)	4.5
15/12	Fixed	North (0)	4.2
16/12	Fixed	North (0)	3.9

The data points ranged from 3.9 to 6.3kwh/m2/day, therefore the mean solar radiation above different elevations was calculated as:

Mean solar radiation = (6.3+ 6.0+ 5.7 + 5.4 + 5.1 + 4.8 + 4.5 + 4.2 + 3.9)/9 = 5.1 kwh/m2/day

The above value corresponds to an elevation/slope of 1.00 degrees which gives the recommended angle of tilt of the PV panel, when the north direction is fixed.

3.3.2. Flow Rate/Discharge

The population data was obtained from the school enrolment as per April 2022 head count. The population for kagadi model, was 955 people (338 boys, 443 girls, 24 staff and approximately 150 nearby community). Uganda's population growth rate is 3% per annum.

The design population of Uganda for 20years is calculated using Equation (1)

$$P_n=P_O\ (1+r)^n \tag{1}$$

Present population (p_o) = 955 persons.
Population growth rate (r) = 3%
Design period (n) = 20 years.
P_n=955(1 + 0.03)20 = 1725 persons

Therefore, the Design population (P_n) = 1725 persons

The daily water demand measured in $m3$/day for KMPS is calculated using Equation (2)

$$Q_d = CP \times P_n \tag{2}$$

Per Capital consumption per day/person (CP) = 18litres
Design population(P_n) = 1725
Daily water demand (Q_d)= 18 x 1725 = 31050 litres/day = 31.05$m3$/day

The sunshine irradiance used for this research design is 5 hours.

The Discharge capacity is calculated using Equation (3)

$$\text{Discharge Capacity (DC)} = Qd/Ts \tag{3}$$

Hours of supply (T_s) = 5hrs
Daily water demand (Q_d) = $31.05m3$/day
Discharge Capacity (D_c) = (31.05m3/day)/5hrs = 6.21 $m3$/day/hour

Therefore, $D_c = 6.21/3600 = 0.001725\ m3/day/sec$

3.3.3. Sizing of the Storage Tank

Size of the tank is calculated using Equation (4)

$$\text{Volume of Tank} = D_c \times T_s \times 1 \quad (4)$$

$$Volume\ of\ the\ Tank = 6.21\times5\times1 = 31.05m3$$
$$= 31.05 \times 1000 = 31050\ litres$$

Tank selected = poly water tank with a capacity of 32000L (2600mm high and diameter of 3950mm)

3.3.4. Static Head

If the discharge point is at a level of 1250 m above the mean sea level (also known as Above Ordnance Datum, AOD) and the reservoir level varies between 1245 AOD and 1240 m AOD. Therefore, the maximum and minimum vertical linear distance between the delivery outlet and the water level (where the pump is to be fixed) is as calculated below:

$Hs{-}max$ =1250m – 1240 = 10m
$Hs{-}min$=1245 – 1245 = 5m

3.3.5. Dynamic Head

The dynamic head (HD) is generated as a result of friction within the system. The pipe material that was selected was PVC pipes which have considerably low friction losses, making them a suitable choice for long pipes because lower friction losses leads to a reduced pump size and subsequent energy consumption.

The dynamic head is calculated using Equation (5)

$$H_D=k*V^2/2g \quad (5)$$

Where,
k = loss coefficient
v = velocity in the pipe (m/sec)
g = acceleration due to gravity (m/$sec2$)

the velocity in pipe is calculated using equation (6)

$$V = Q/A \quad (6)$$

where,
Q = flow rate through the pipe ($m3$//sec) =Dc
A = pipe cross sectional area (CSA) ($m2$)

3.3.6. Pipe Size Selection

The selected pipe diameter for this design is 7.5cm. Smaller diameters were selected because of the long piping, the piping cost can be considerably more expensive than the pumping installation and a pipe size smaller matched to a larger sized pump can reduce the investment but increases the running cost which is better because we are using solar PV to power the pump.

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Using equation (6) and a pipe diameter of 10cm, velocity in the pipe is then given as:
V = 0.001725 m3/day/sec / (π×0.018752) = 1.5618 m/sec

Therefore, the dynamic head reduced to;
$H_D = (K/2g)$ × v2 = (K×1.56182) / (2×9.81) = 0.1243K

The loss coefficient K is made up of two elements as shown in Equation (7)

$$K = K\ fittings + K\ pipe \tag{7}$$

K fittings is associated with the fittings used in the pipework's of the system to pump the water from reservoir to the receiving tank. Values were obtained from standard tables and total K fittings. Values were calculated by adding all the K fittings values for each individual fitting within the system. Table 3 shows the calculation of K fittings for the system under consideration.

Table 3. Values of Kfittings Pipes Used for the Design

Fitting	No of Items	$K_{fitting}$	Item Total
Pipe entrance (bell mouth)	1	0.05	0.05
90^0 bend (short radius)	6	0.75	4.5
45^0 bend short radius)	2	0.3	0.6
Butterfly valve (fully open)	2	0.3	0.6
Non return valve	1	1.0	1.0
Bell mouth outlet	1	0.2	0.2
		Total k $_{fitting}$ valve	**6.95**

The total K fittings for the system under consideration for this design is 6.95.

K pipe is associated with the straight lengths of pipe used within the system and is calculated using Equation (8)

$$K_{pipe}=fL/D \tag{8}$$

Where,
f = friction coefficient
L = pipe length (m)
D = pipe diameter (m)

The friction coefficient f can be found using a modified version of the Colebrook White Equation as shown in Equation (9)

$$f = \{(0.25)/\log [(k /3.7\times D) + (5.74 /Re0.9)]\}^2 \tag{9}$$

Where,
k = Roughness factor (m)
Re = Reynolds number

Reynolds number is a dimensionless quantity associated with the smoothness of flow of a fluid and relating to the energy absorbed within the fluid as it moves. For any flow in pipe, Reynolds number can be calculated using equation (10)

$$Re = ÞVD/\mu \tag{10}$$

Fluid density(Þ) = 1 kg/m3
Velocity in the pipe (V) = 1.5618 m/sec
Diameter of the pipe (D)= 0.075 m

Kinematic viscosity (µ) = 1.31×10−6 m 2 /s (µ of water at room temperature is 1.31 × 10−6 m2/ sec)
Re = (1×1.5618 ×0.075)/ (1.31×10−6)
= 8.9416 × 104

The pipe roughness factor k is a standard value obtained from standard tables and is based upon the material of the pipe, including any internal coatings and the internal condition of the pipeline.

Table 4. Pipe Materials and Common Pipe Roughness Values

Material	**K (mm)**	**K (inches)**
Concrete	0.3-3.0	0.012-0.12
Cast iron	0.26	0.010
Galvanized iron	0.15	0.006
Asphalted cast iron	0.12	0.0048
Commercial or welded steal	0.045	0.0018
Pvc, glas, other drawn tubing	0.0015	0.00006

Equation (9) was used to obtain the friction coefficient of the design as:

$$f = \left(\frac{0.25}{\log\left[\frac{k}{3.7*D} + \frac{5.74}{R_e^{0.9}}\right]}\right)^2$$

$$f = \left(\frac{0.25}{\log\left[\frac{1.5*10^{-6}}{3.7*0.075} + \frac{5.74}{(8.9416*10^{4})^{0.9}}\right]}\right)^2$$

f = 0.002298

Given the length of the pipe as 100m and the diameter of the same as 0.075m then equation (9) is used as follow:

$$K_{pipe} = \frac{fL}{D}$$

$$K_{pipe} = \frac{0.002298*100}{0.0075}$$

= 3.064

Finally, using Equation (7), the total K value for the system is:

K = 3.064 +6.95=10.014

The dynamic head is calculated using Equation (5) as follow:

$$H_D = k*\frac{V^2}{2g}$$

$$H_D = 10.014*\frac{1.5618^2}{(2*9.81)} = 1.245\text{m}$$

The maximum and minimum total differential head is calculated using equation (11) and (12) respectively,

Dhmin =$Htotal{-}max$ = 10m+1.245 = 11.245m (11)
Dhmax = $Htotal{-}min$ = 5m+1.245 = 6.245m (12)

3.3.7. Sizing and Selection of PV Module

The size of a PV array was calculated using Equation (13)

$$E = 2.725 * 10^{-3} * Q * H \tag{13}$$

E_{max} = 0.002725×11.245×0.001725 × 3600 = 0.19029 (kWh/day)
E_{min} = 0.002725×6.245×0.001725 x 3600= 0.10568 (kWh/day)

The solar array required in KWp is calculated using equation (14)

$$\text{The solar array required (kWp)} = \frac{\text{Hydraulic energy required (kWh/day)}}{\text{F} \times \text{E} \times \text{Average daily solar irradiation}\left(\frac{\frac{\text{kWh}}{\text{m}^2}}{\text{day}}\right)} \tag{14}$$

$$E_{s\,max} = \frac{\text{Eh max}}{\text{Av.Is} \times \text{F} \times \text{E}} \tag{15}$$

Eh max = 0.19029
Eh min = 0.10568
Array mismatch factor (F) on average = 0.85
Daily subsystem efficiency (E = 0.25 – 0.40; mean = 0.325
$Av.Is$ = 1534/ 50×30 = 1.0227 (KWh/m²/day)
$E_{s\,max} = \frac{\text{Eh max}}{\text{Av.Is} \times \text{F} \times \text{E}}$ = 0.19029 / (1.0227 ×0.85 ×0.325) =0.6735 (kWh/day)
$Es\ min = \frac{\text{Eh min}}{\text{Av.Is} \times \text{F} \times \text{E}}$ = 0.10568 / (1.0227 ×0.85×0.325) = 0.37406 (kWh/day)
$E_{s\,mean} = (E_{s\,max} + E_{s\,min})/2$ = (0.6735 +0.37406) / 2 =0.52378 (KWh/day)

Assuming, the actual sunshine hours is 5 hrs in a day
Total wattage of PV panel = 523.78/ 5 = 104.756 W
Number of solar panels required = 50W × 4 panels = 200W power

The panel model that was selected was YL50 with rated power of 50W, open circuit voltage of 22 V and short circuit current of 3.1A.
The size of each battery = 500Wh / 22V= 22.8A

Medium size batteries were selected, 30 Amp hours' capacity each, giving a total of 120A hours.

3.3.8. The Solar Charge Controller Selection

Solar charger controller rating = Total short circuit current of PV array × 1.3
Solar charger controller rating = 3.1×1.3 = 4.03A

The appropriate change controller used for this design is SUNDAYA Apple 10A charge controller [4], [21], [22].

3.3.9. Pump Power Requirement

The power requirement for the pump is calculated using equation (16)

$$P = \frac{Q * g * \rho * H}{pump\ efficiency} \tag{16}$$

Discharge (Q) = 0.001725 m³/day/sec
Acceleration due to gravity (g) = 9.81 m/sec²
density of water (ρ) = 1000 kg/m³
Total Differential Head (H) = $H_{total-mean}$ = (11.245m +6.245)/2 = 8.745m
Assuming a pump efficiency = 70%
$P = \frac{0.001725 * 9.81 * 1000 * 8.745}{0.7}$ = 211.407W

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3.3.10. Pump Selection

During pump selection, the Specification sheet prepared by solar water pump manufacturer was adopted and the values are as follow:

Flowrate (Q) = 6.21 m^3/day/hour.
Total Differential Head (H) = $H_{total-mean}$ = 8.745m
Pump power required (P) = 211.407W

Table 5. Photovoltaic Pumping System Specifications

Motor Pump / Configuration	**Output (m^3/day/hr)**	**Head (m)**	**Solar Array (W)**	**System Price US$ FOB**
Submersible	40	20	2000	2000-2500
Motor Pump-Lorentz centrifugal solar pump	25	20	1200	6000-7000
Surface motor/ submerged pump	60	7	840	1500-2000
Reciprocating positive displacement pump	6	100	1200	2500-3000
Floating motor/pump set	100	3	530	2000
	10	3	85	1000
Surface suction pump	40	4	350	1500

3.3.11. Cost benefit Analysis

Data in Table 6 was observed using the following the normal cost mathematical analysis and formula.

Table 6. Cost Benefit Analysis of Solar and Diesel Pumping Systems

Systems	**Initial Capital Cost (UGX)**	**Fuel Cost/Litre (UGX)**	**Consumption Rate/ kilowatts/day**	**Operating cost/year (UGX)**	**O&M cost in 20years**	**Total NPC (UGX)**
Solar Pump	2587680			1149385	22987700	25575380
Diesel Pumps	3500000	3440	3litres=3x1.25	65400090	1308001800	1308351800

Initial capital cost = First cost for each option – assumes same pump costs while,

Operation cost and management cost (O&M)/year = the average O&M costs per year which excludes pump replacement costs which would be same for both.

Net Present Cost = The present value of the cost of installing and operating the system over the lifetime of the project (also referred to as lifecycle cost).

Furthermore, the Cost of running the solar water pump and the diesel water pump for the period of 20years were calculated and compared. It was observed that the net benefit of running solar pump powered system against diesel water powered system is 1282776420UGX.

4. Finding and Discussion

The solar water pump system was designed using mean solar radiation of 5.1 Kwh which corresponds to an elevation/slope of 1.00 degrees. The 955 population of KMPS was obtained from the school enrolment of 2022 head count. The 1725 of 20 years' population of KMPS used in the design was obtained using the Uganda's population growth rate of 3.0% per annum. The irradiance of 5.1Kwh used in this research design gave water flow rate of 6.21 $m3$/day/hour.

The daily water requirement was found to be 18 litres per person per day [23]. The average total differential head was found to be 8.745m and Total wattage of PV panel is 104.756 W. The Number of YL50 solar panels used in this design for effective and efficient water pumping is 50W panel by 4 pieces which when cascaded will give 200W power. Backup battery of 120A hours and SUNDAYA Apple 10A charge controller rating of 4.03A was used for this design. The power requirement for the pump was calculated to be 211.407W whereas the pump efficiency is assumed to be 70%. The cost benefit analysis between diesel pump system and solar pump systems will give 1282776420UGX for the period of 20years.

Therefore, the cost of running solar pumping system is the most economical and the best for adoption.

5. Conclusion

The collected and analyzed climatic data from the metrological site, calculated solar water pumping requirements showed that solar power is an alternative source of energy and a viable solution for the water abstraction problems experienced by Kagadi Model Primary School and the school community. This developed system will help to distribute water fairly to the KMPS and its environ at very a cheap and steady manner for the pump will be powered with solar energy of 200Wp. The solar water pump of 211.407W was energized using solar energy system to pump water into the storage facility (reservoir) before distributing it by the help of gravitational force to various locations for consumption. This designed solar powered energy system when implemented will curb the problem of water scarcity, provide clean water and reduce unhygienic nature of the environment as it in line with one of the Sustainable Development Goals (SDGs).

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