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Design of pumped water storage solar–hydropower system with surface water source pumping mechanism

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Abstract

In this paper, design of pumped water storage solar–hydro-power system with surface water source pumping mechanism is presented. The design considered a 750 kVA (which is 600 kW) power system that can run for 24 hours. Hence, the load profile consists of a 750 kVA by 24 hours per day electrical load which gave daily energy demand of daily energy of 14,400 kWh. The design was conducted using 21 years (2003 to 2023) meteorological dataset of the case study site at Akwa Ibom State University (AKSU) main campus at Ikot Akpadem with the latitude and longitude of 4.6214 and 7.7639 respectively. Detailed descriptive statistical analysis of the dataset was done. The design results show that the water storage capacity of m^3 is required for the 3 days of power sutonomy. About 50 water pumps each reated at 59.797 kW (approximately 60 kW) are used for the water pump while 10 water pumps each reated at 2989.827 kW (approximately3 kW) are used for the top up water segment. The hydro power with water top up has effiecncy of 0.623 (or 62.3%) and requires 23111.570 kWh of energy every day from the solar power system. The solar power is designed with the mean solar radiation value of 6.16534 and daily energy demand of 23,111.57 kWh which is the energy demand form the hydro power segment. The PV power rating is 5,174.29 kW. With 200 Wp PV module, a total of 25,871.46 PV modules were required to supply the needed power. The daily energy yield of the PV array was 31,901.29 kWh and the operating efficiency of the PV system was 0.72447 (or 72.4%). The ideas presented in this are useful for the design of modern solar hydro power plants that can be installed and sustained even in areas with water shortages.

Keyword: Solar–Hydropower System; Meteorological Data; Water Top Up Mechanism; Surface Water Pumping Mechanism; Pumped Water Storage Solar–Hydro Power; Hybrid Power Generating System

1. Introduction

In the last few decades, there has been growing concern about the detrimental impact of ozone layer depletion and the need to curb the trend by avoiding or curtailing processes that cause it [1][2]. The global warming and extreme weather conditions with their wide spread negative impacts across the globe has given credence to this view. Approaches to address the situation include reduction of carbon emission into the air [3,4,5]. In this wise, energy sources that requires much carbon emission are increasingly being discouraged across the globe.

Similarly, researchers have identified the traditional large scale fossil fuel energy sources as not sustainable due to their detrimental consequence on the environment [6,7]. Also, it has been noted that such energy sources are not renewable, and hence they are not sustainable in its utilization. The depletion of such energy resources as fossil fuel becomes another concern as the growing global population and rising energy demand will continue to increase with the danger of growing energy shortage [8,9]. Accordingly, the focus in the last few decades has been on renewable green energy

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source which environmentally friendly and at the same time do no deplete with use [7]. Among such energy sources are solar photovoltaic (SPV), solar thermal (STM), wind energy, tidal energy, hydro energy, among others [7]. The SPV requires the use of a photovoltaic (PV) device to capture solar radiation and convert it to electrical energy [8]. The STM requires the use of solar collector to convert solar radiation energy to heat which can be used to generate energy by heating water to steam or other substance to generate energy [9]. The wind energy requires the use of wind turbine which rotates due to wind and thereby generate electricity by the turning of magnetic field with an enclosed electric wire coil [10]. Similar approach is used in hydro turbine where the turbine is turned by the flow of water [11,12,13].

Among the numerous renewable energy sources, the hydro power generation option has been widely adopted with large scale energy production already installed across the globe. In many nations, the hydro power plants constitutes the major power source which are fed into the national grid [12]. However, as population grows and economies of many nations are not enough to ensure adequate generation and supply of the energy from the national grid to the good number of locations in their nation, many people have resorted to alternative energy supply to meet their energy demand [13,14,15].

Specifically, in Nigeria, over 40 % of the entire population have no access to the electricity from the national grid [14]. As such, the use of fossil fuel electricity generators like diesel, petrol and gas plants have grown to alarming degree over the years. However, as the cost of the fossil fuel increases, coupled with the rising cost of energy from the national grid, many energy users in Nigeria are turning to renewable source with solar photovoltaic being the top on the list of alternative energy option across Nigeria [16,17,18]. One major reason for such wide adoption of SPV is because the solar radiation across the nation is adequate for energy generation all through the year. Besides, there is continuous drop in the cost of SPV plant implementation [16].

While solar energy option is viable, its major drawback is the stochastic nature of the solar radiation upon which the SPV energy generation depends [19,20,23]. Moreover, the solar radiation is only available only during the day; there is no significant energy production in the early hours of the day, the evening part of the day and the entire night hours. Furthermore, when it rains, the solar radiation is barely available for energy generation. All these factors necessitated the use of energy storage facilities for energy backup; to supply continues energy to the load even when the solar radiation is not available. One common energy storage option is the battery bank, but researchers have identified that the lifespan of battery storage is short and the cost of battery is high making it not cost effective for large scale energy storage. However, battery storage is very popular because of its portability, availability in sizes that can be assembled to accomplish power supply of any capacity[24,25,26].

On the other hand, hydro energy storage has been developed over the years; some occurring naturally in terms of elevated water reservoirs serving as stored energy which can be converted to electric energy by using a hydro turbine [27,28,29]. Notably, nowadays, pumped water storage approach is being used to implement the hydro energy storage concept. The combination of solar and hydro energy power solution is the main focus of this research. Specifically, this work focus on the design of pumped water storage solar–hydropower system with surface water source pumping mechanism. The details of the analytical models used as well as the statistical analysis of the meteorological dataset of the installation site are provided [30,31].

2. Methodology

2.1. The system model for the solar-hydro power plant

In this work, the focus is on design of pumped water storage solar–hydropower system with surface water source pumping mechanism. The pumped water storage solar–hydropower system with surface water source pumping mechanism has electric load which is powered by the hydro power generating segment of the system, as shown in the system model of Figure 1.

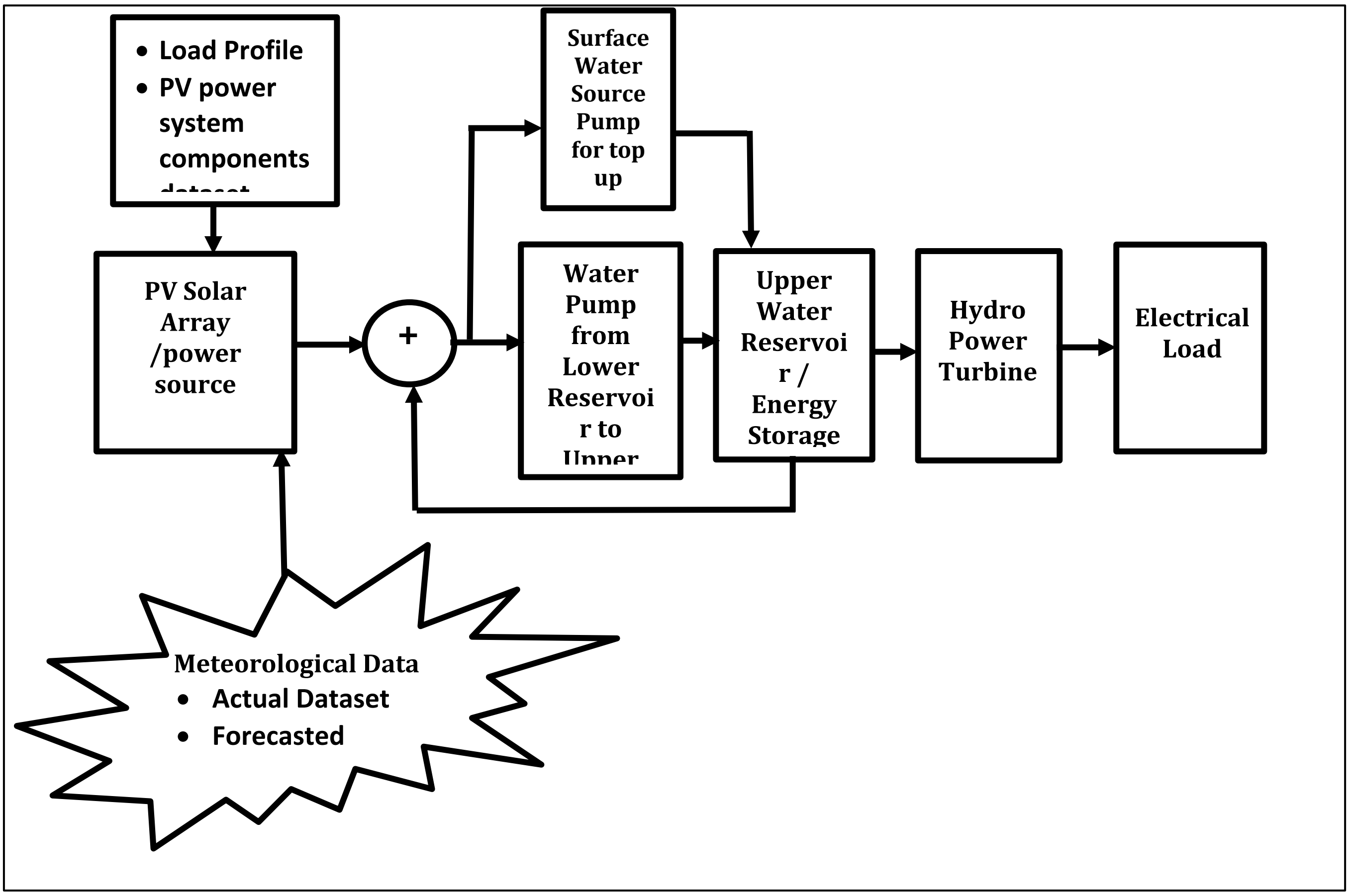

Figure 1 The system model for the pumped water storage solar–hydro power system with surface water source pumping mechanism

The hydro power generator is driven by pumped water stored in the upper reservoir. The water is pumped by solar power system which drives two sets of water pumps, namely the water pump for pumping the initial water from the surface water reservoir or stream to the upper reservoir. Also, this pump is used to top up the water in the upper reservoir to compensate for water losses due to evaporation and other causes. Also, the second set of the pumping system is the main pump which steadily pumps water from the lower reservoir to the upper reservoir. The water pumping mechanism is controlled by the system based on the solar power energy generation and the feedback from the reservoir in terms of water level drop or need to compensate for water losses.

Meanwhile, the sizing of the solar power segment of the system is based on meteorological dataset, the load profile and the solar-hydro power plant components dataset. All these dataset are used in determining the actual component sizes for the PV power system. Again, the system model showed that the meteorological dataset used included the actual time series dataset and the machine learning forecasted dataset.

2.2. The study site and the load demand profile for the hydro power segment

The case study solar–hydro installation site is at Akwa Ibom State University (AKSU) main campus at Ikot Akpadem with the latitude and longitude of 4.6214 and 7.7639 respectively, as shown in the Google map site visualization presented in Figure 2. The campus is located to a stream which has sufficient water that can be pumped to a reservoir for hydro power plant. The stream has water all through the year. Hence, there can be water to top up the water in the reservoir in occasions of water losses due to evaporation and other factors.

The design considered a 750 kVA (which is 600 kW) power system that can run for 24 hours. Hence, the load profile consists of a 750 kVA by 24 hours per day electrical load. Let the power demand per day in kW/day be denoted as Pkwpday, in kVA/day be denoted as PkVApday, the energy demand per day in kWh/day be denoted as Epday, the operating power factor be denoted as pf and the number of operating hours per day in hours be denoted as hpday (where hpday = 24 hours) then the listed parameters are related as shown in Equation 1 and Equation 2;

$$\text{Pkwpday} = (\text{PkVApday})(pf) \quad (1)$$

$$\text{Epday} = (\text{Pkwpday})(\text{hpday}) \quad (2)$$

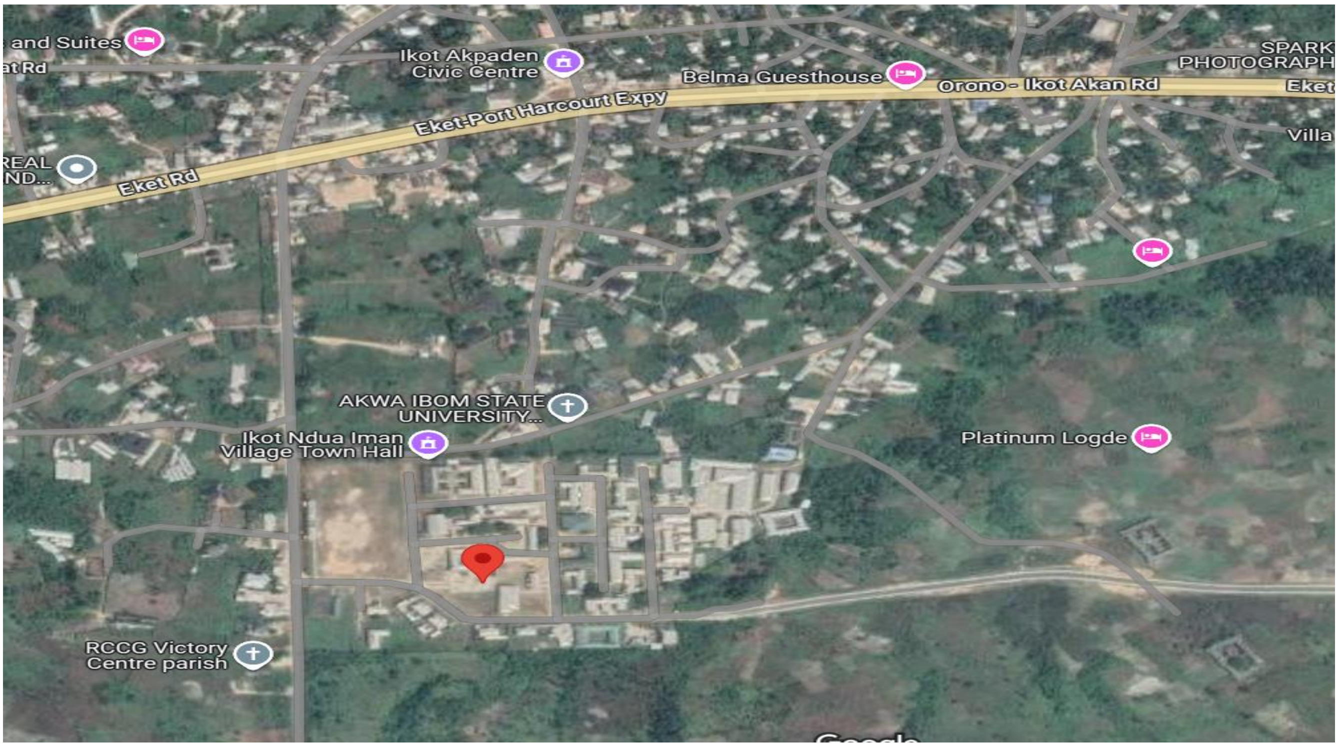

Figure 2 The study solar–hydro installation site at AKSU with the latitude and longitude of 4.6214 and 7.7639 respectively

2.3. Acquisition of the meteorological datasets of the study site and descriptive analysis of the datasets

The meteorological dataset for the study site were download from NASA portal by using the NASA online POWER Data Access Viewer tool. The specific meteorological considered are the daily mean global solar radiation on the horizontal plane and the daily mean atmospheric temperature at 2 m above sea level. The 21 years (2003 to 2023) data for each of the three parameters were downloaded in CSV format.

The 21 years daily mean solar radiation dataset download from NASA portal has 7,670 daily mean solar radiation data records which is plotted in Figure 3.4. The descriptive data analysis of the dataset was also conducted with online tool available at https://www.statskingdom.com and the summary of the descriptive data analysis is presented in Table 1, as well as in Table 2, Table 3, Figure 4, Figure 5 and Figure 6. There are 46 outliers which are mainly values below the lower outlier fence. No data above the mean is an outlier. The annual mean of the daily solar radiation dataset is 6.255 W-hr/m^2/day.

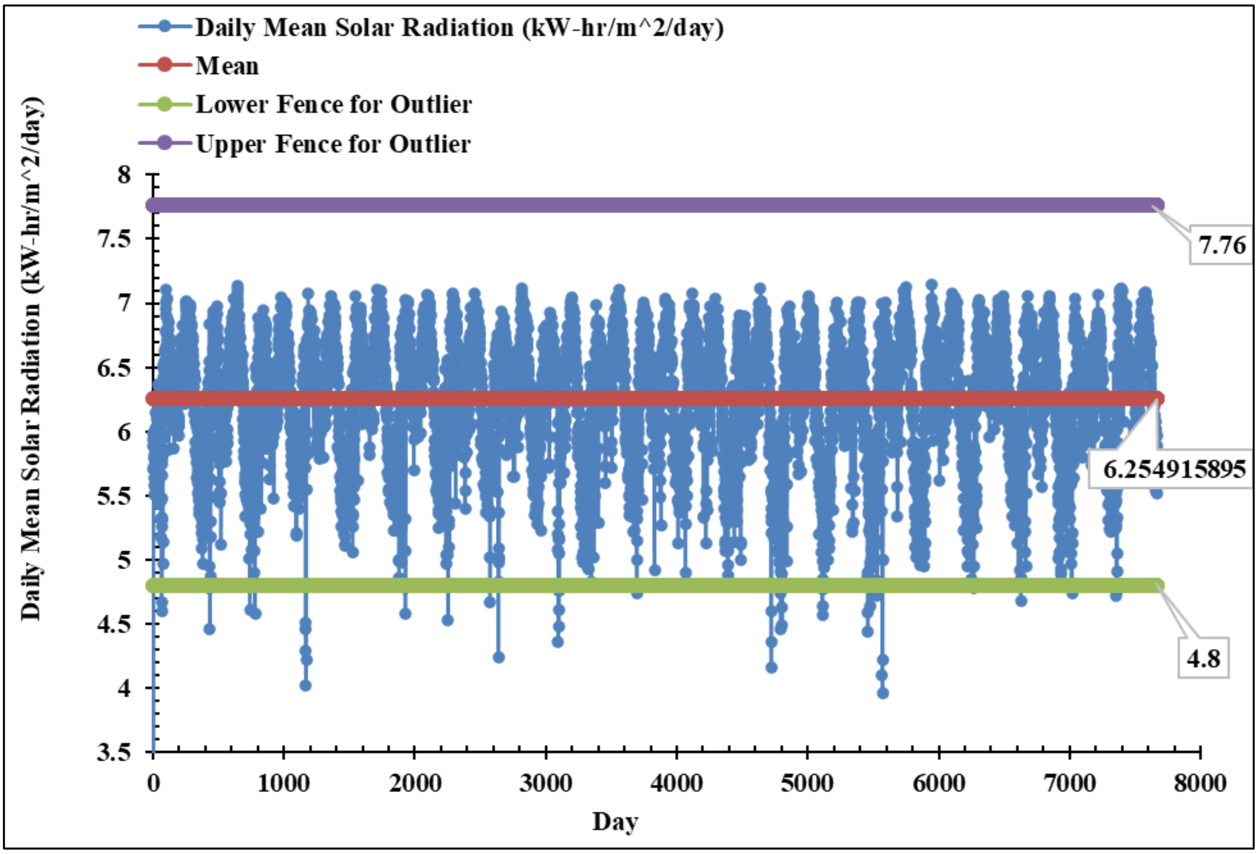

Figure 3 Scatter plot of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

Table 1 The summary of the descriptive analysis of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

Groups	Daily Mean Solar Radiation (kW-hr/m^2/day)
Number of observations	7,670
Number of missing values	0
Minimum	3.96
Maximum	7.15
Range	3.19
Mean (xÌ„)	6.2549
Mode	6.66 (appears 79 times)
Standard Deviation (S)	0.4961
Q1	5.91
Median	6.33
Q3	6.65
Interquartile range	0.74
Skewness	-0.6843

Table 2 The summary of the outliers in the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

S/N	Daily mean solar radiation (kW-hr/m^2/day) considered an outlier	S/N	Daily mean solar radiation (kW-hr/m^2/day) considered an outlier	S/N	Daily mean solar radiation (kW-hr/m^2/day) considered an outlier
1	3.96	17	4.51	33	4.72
2	4.02	18	4.53	34	4.72
3	4.1	19	4.57	35	4.74
4	4.16	20	4.58	36	4.74
5	4.22	21	4.58	37	4.74
6	4.22	22	4.59	38	4.76
7	4.24	23	4.6	39	4.76
8	4.29	24	4.6	40	4.76
9	4.36	25	4.61	41	4.77
10	4.36	26	4.61	42	4.77
11	4.44	27	4.63	43	4.78
12	4.46	28	4.64	44	4.78
13	4.46	29	4.64	45	4.78
14	4.46	30	4.67	46	4.78
15	4.48	31	4.67		
16	4.49	32	4.68		

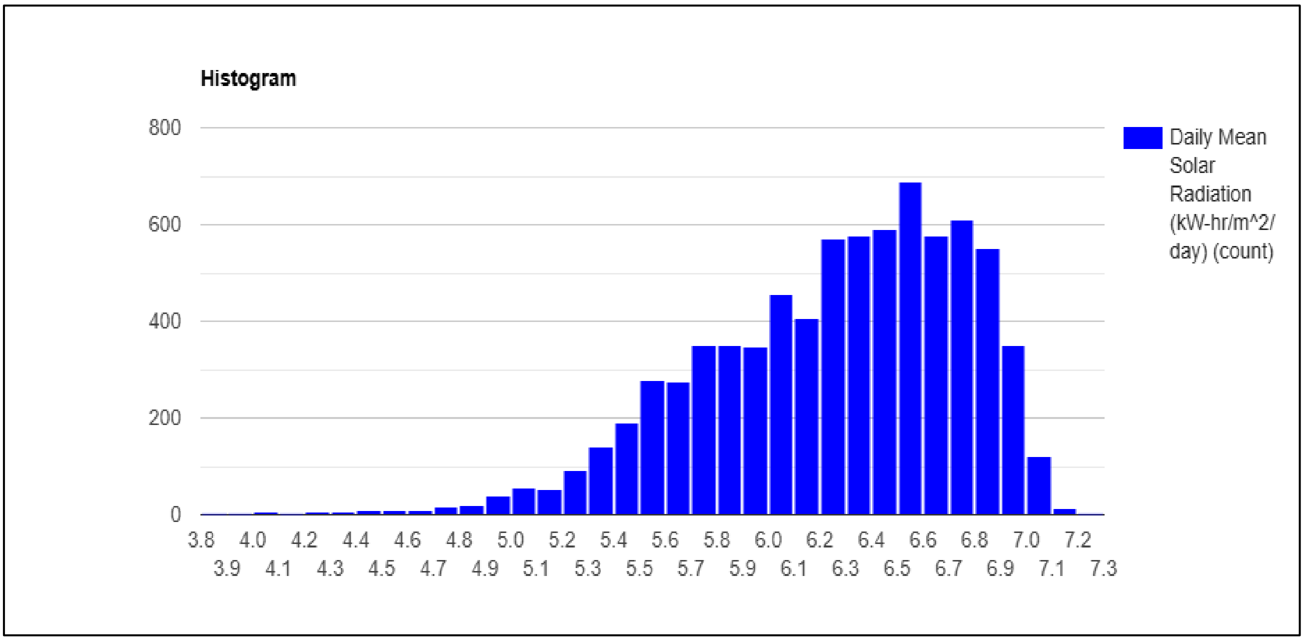

Figure 4 The histogram of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

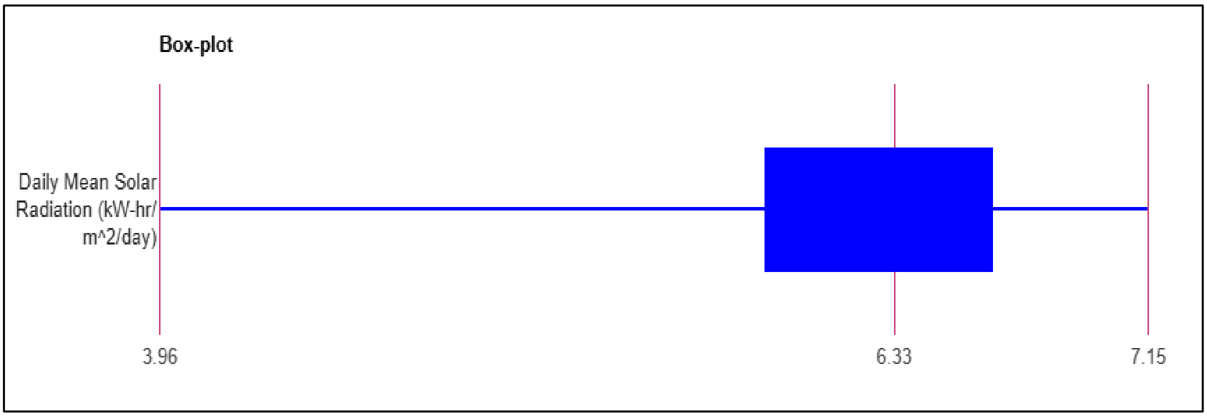

Figure 5 The box plot of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

Table 3 The summary of the percentile analysis of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

Percentile	Value
0th	3.96
10th	5.56
20th	5.8
30th	6.02
40th	6.2
50th	6.33
60th	6.47
70th	6.59
80th	6.71
90th	6.84
100th	7.15

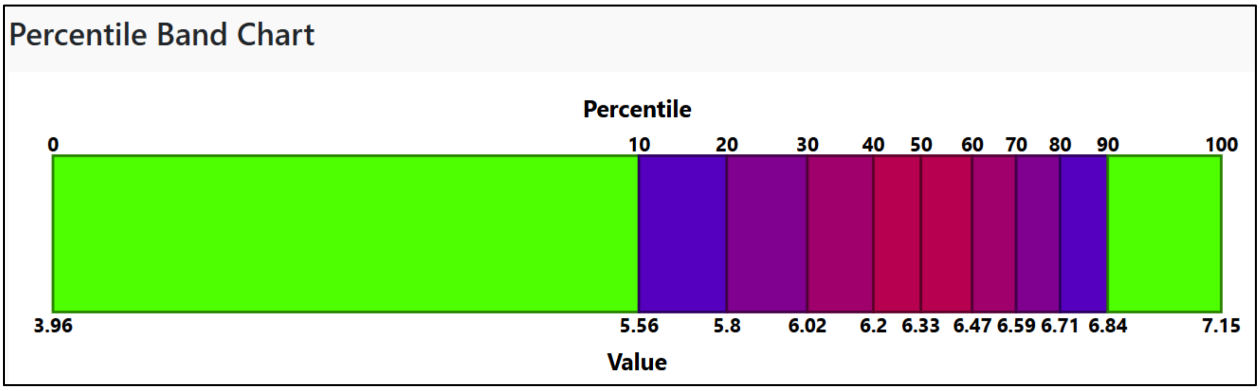

Figure 6 The percentile band plot of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

Equally, the 21 years daily mean atmospheric temperature dataset download from NASA portal has 7,670 daily mean atmospheric temperature data records which is plotted in Figure 3.8. The descriptive data analysis of the dataset was also conducted with online tool available at https://www.statskingdom.com and the summary of the descriptive data analysis is presented in Table 4, as well as in Table 5, Figure 9, Figure 10 and Figure 11. There are five outliers which are mainly values below the lower outlier fence. No data above the mean is an outlier. The annual mean of the daily atmospheric temperature dataset is 26.856 °C.

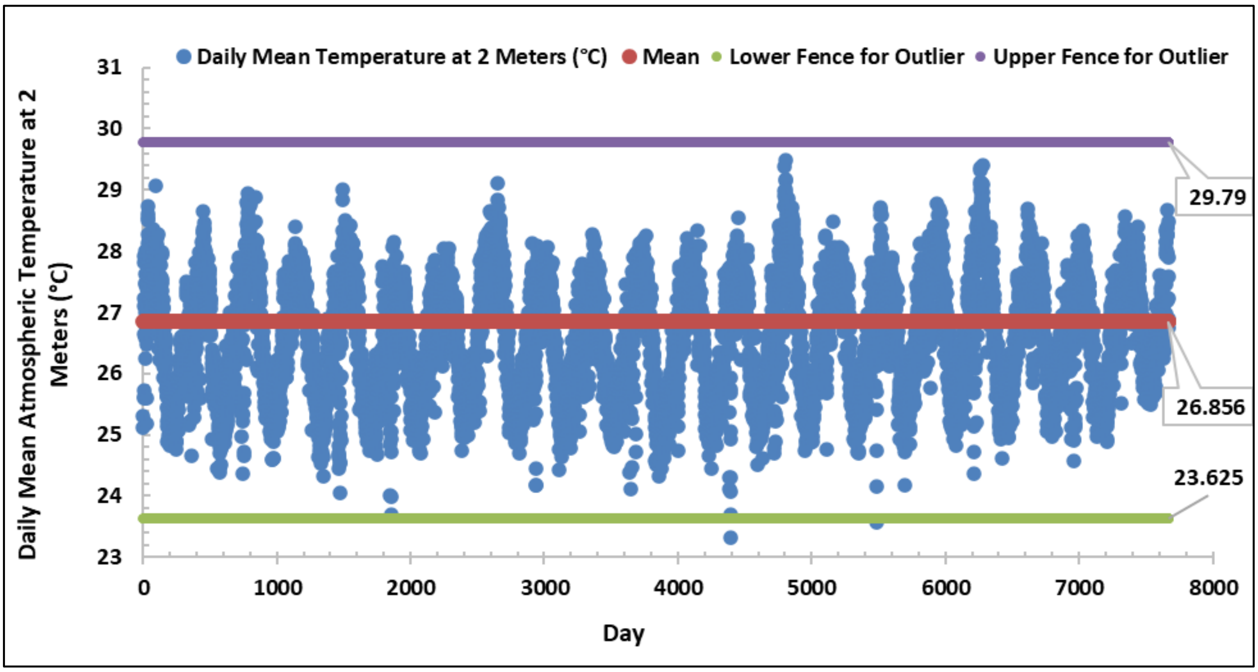

Figure 7 Scatter plot of the 7,670 data records of the 21 years daily mean atmospheric temperature dataset download from NASA portal

Table 4 The summary of the descriptive analysis of the 7,670 data records of the 21 years daily mean atmospheric temperature dataset download from NASA portal

Groups	Daily Mean Temperature at 2 Meters (°C)	
Num of observations	7,670	
Num of missing values	0	
Minimum	22.48	
Maximum	29.48	
Range	7	
Mean (xÌ„)	26.5538	
Mode	25.69 (appears 58 times)	
Standard Deviation (S)	0.9693	
Q1	25.73	
Median	26.57	
Q3	27.33	
Interquartile range	1.6	
Skewness	0.000302	
Outliers	22.48,22.49, 22.62, 22.8,23.33	

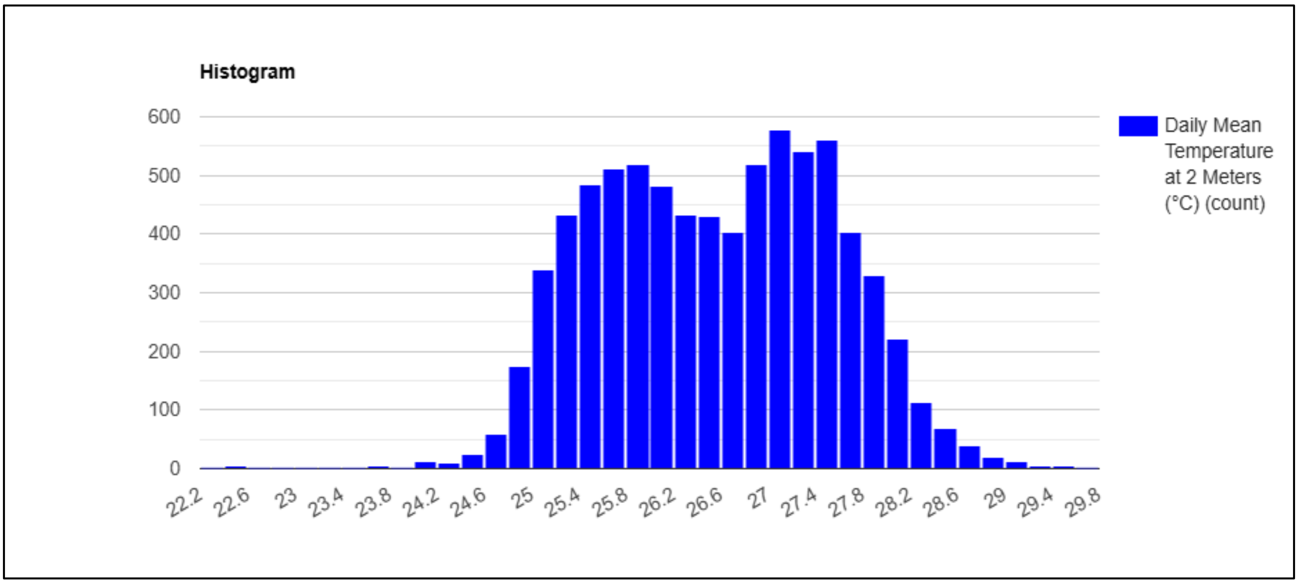

Figure 8 The histogram of the 7,670 data records of the 21 years daily mean atmospheric temperature dataset download from NASA portal

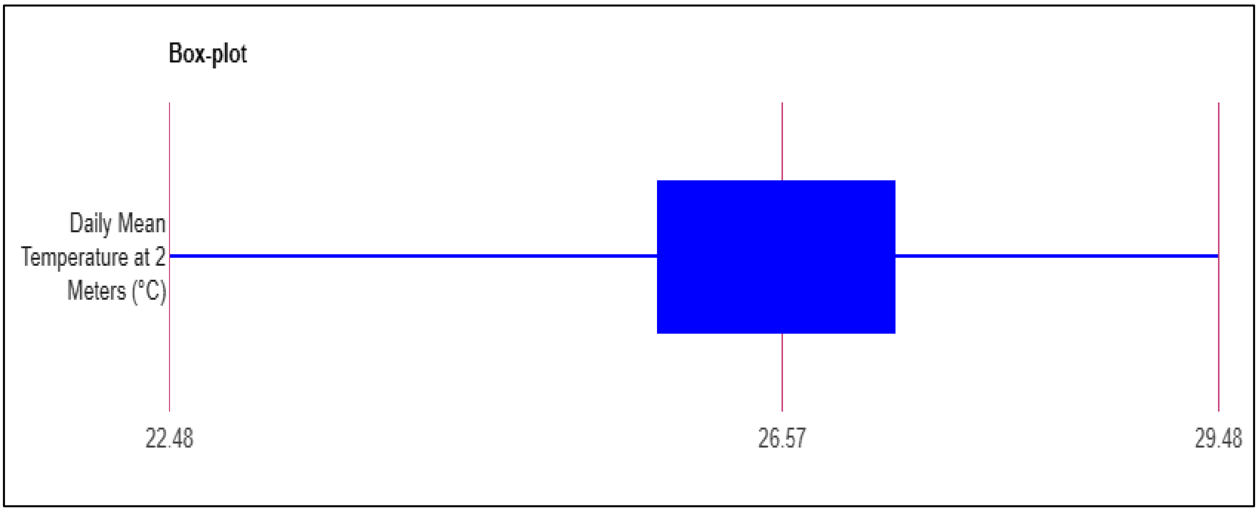

Figure 9 The box plot of the 7,670 data records of the 21 years daily mean atmospheric temperature dataset download from NASA portal

Table 5 The summary of the percentile analysis of the 7,670 data records of the 21 years daily mean atmospheric temperature dataset download from NASA portal

Percentile	Value
0th	22.48
10th	25.26
20th	25.6
30th	25.9
40th	26.22
50th	26.57
60th	26.92

70th	27.19
80th	27.47
90th	27.8
100th	29.48

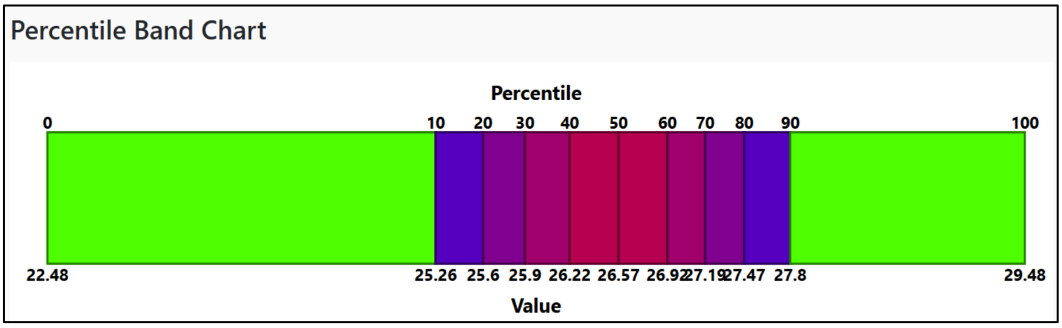

Figure 10 The percentile band plot of the 7,670 data records of the 21 years daily mean solar radiation dataset download from NASA portal

2.4. Determination of the solar-hydro power components sizes and the sizes of the pumped water storage reservoirs

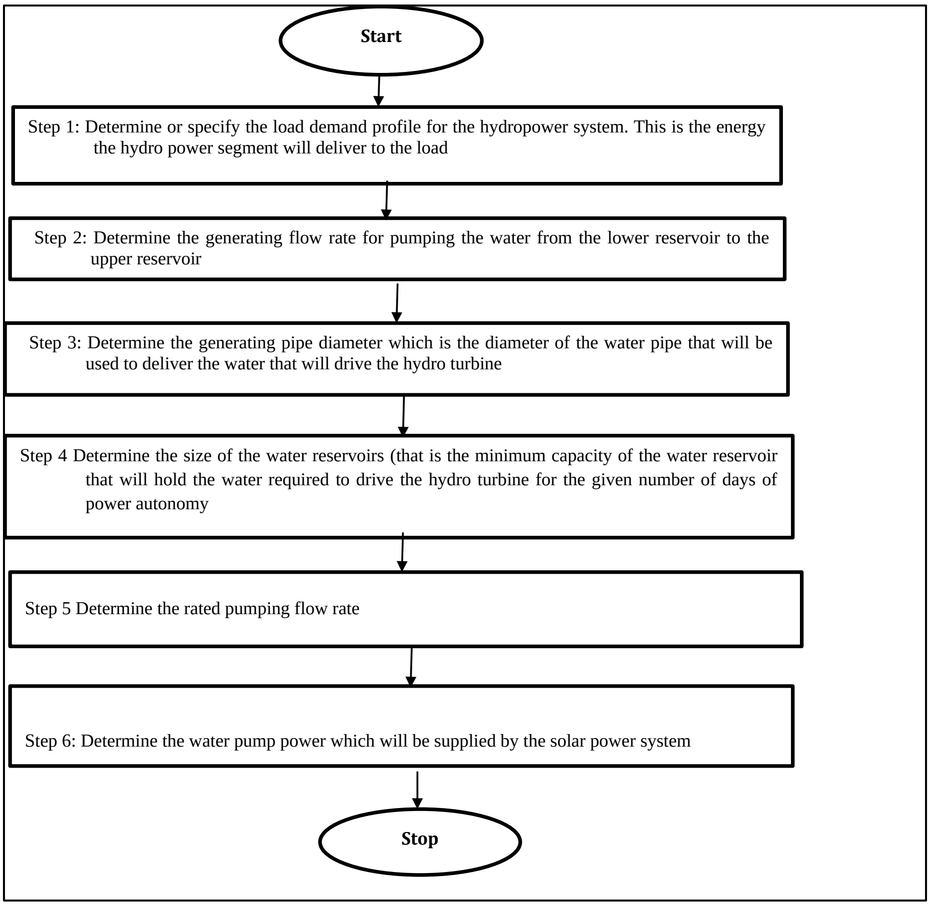

Figure 11 The flowchart used to determine the hydro power components sizes and the sizes of the pumped water storage reservoirs

This section captures the analytical models and the flowchart used to determine the hydro power components sizes and the sizes of the pumped water storage reservoirs. The flowchart if presented in Figure 11 followed by the analytical models.

2.4.1. Sizing of the solar-hydro power generating flow rate and the hydro power generating pipe diameter

The power, Pkwpday is expected to be generated by hydro power turbine in order to meet the daily energy demand. Let the flow rate of the hydro power generator be denoted as Q_g and its unit expressed in m^3/s , then (Deele, Ozuomba and Okpura, 2019);

$$Q_g = \frac{PrKw}{(\rho)(g)(\eta_t)(H_g)} \quad (3)$$

Where, ρ is used to represent the density of the water at 25 °C, η_t is used to represent the hydro power turbine efficiency, g is used to represent the acceleration due to gravity and H_g is used to represent the rated water head. Let the area of the pipe used to deliver water to the water turbine be denoted as, A (unit expressed in m^2), V is the velocity of the water flowing in the pipe (in m/s), and d_g is the diameter (unit expressed in m) of the pipe used to deliver water to the hydro power generating turbine, then;

$$A = \frac{\pi {d_g}^2}{4} = \frac{Q_g}{V} \quad (4)$$

Therefore,

$$d_g = \sqrt{\frac{4(Q_g)}{\pi(V)}} \quad (5)$$

2.4.2. Sizing of the hydro power water reservoirs size

Let the days of power autonomy (expressed in days) be denoted as daut, let the reservoir storage capacity safety factor be denoted as fsfrsv, the flow rate per day be denoted as Q_{gdy} and the reservoir capacity (m^3) be denoted as Crsv, then;

$$Q_{gdy} = (86400)(Q_g)(\text{fsfrsv}) \quad (6)$$

$$\text{Crsv} = Q_{gdy}(\text{daut}) = (86400)(Q_g)(\text{fsfrsv})(\text{daut}) \quad (7)$$

2.4.3. Sizing of the rated pumping flow rate and the water pump power

Let the power required to pump water be denoted as P_{pr} (expressed in unit of kW). This power is required to pump the water to the upper reservoir from the lower water reservoir and it is computed as follows (Deele, Ozuomba and Okpura, 2019):

$$P_{pr} = \frac{(\rho)(g)(Q_p)[H_p + H_{p1}]}{\eta_p} \quad (8)$$

Where η_p is the pump efficiency, Q_p is the pump rated flow rate expressed in m^3/s, H_p is the rated pumping head expressed in m and H_{p1} is the major head losses expressed in m, then;

$$Q_p = \frac{Q_{gdy}}{(60)(60)(SH)} \quad (9)$$

Where SH denotes the mean sun hours per day which invariably indicates the number of hours which the solar power will use to power the pump per day.

The head losses (H_{p1}) is computed by using the Darcy-Weisbach head loss equation given as;

$$\mathrm{H_{p1}} = \frac{(f_{dm})(H_p)({V_p}^2)}{2(g)(d_p)} \quad (10)$$

Where; f_{dm} is used to indicate the Darcy-Weisbach friction factor, H_p is used to indicate the rated pumping head (m), d_p is used to indicate the pipe diameter (m) and V_p is used to indicate the fluid velocity in the pumping pipe (m/s) , then;

$$V_p = \frac{Q_p}{A_p} = \frac{Q_p}{\left(\frac{\pi d_p{}^2}{4}\right)} \qquad (11)$$

Then;

$$f_{dm} = 0.25\left\{\log\left(\frac{\epsilon/d_p}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right\}^{-2} \qquad (12)$$

Where ϵ is used to indicate the pipe roughness, Re is used to indicate the Reynold number where,

$$Re = \frac{(V_p)(d_p)}{\upsilon} \qquad (13)$$

Where υ is used to indicate kinematic viscosity of water at 25 °C.

Let N_{pllp} be used to indicate the number of parallel pumps used, $Q_{pN_{pllp}}$ be used to indicate the flow rate of each of the N_{pllp} pumps, then;

$$Q_{pN_{pllp}} = \frac{Q_p}{N_{pllp}} \qquad (14)$$

Therefore, based on the multiple pumps to be used, the power rating of each of the pump which is represented as P_{pllp} is given as;

$$P_{pllp} = \frac{(997)(9.81)\left(Q_{pN_{pllp}}\right)[H_p + H_{p1}]}{\eta_p} \qquad (15)$$

2.4.4. Sizing of the source water top up rated pumping flow rate and water pump power

Let the power required to pump water from the source be denoted as P_{prS} (expressed in unit of kW). This power is required to pump the top up water from the source to the upper reservoir and it is computed as follows (Deele, Ozuomba and Okpura, 2019):

$$P_{prS} = \frac{(\rho)(g)(Q_{pS})[H_{pS} + H_{pS1}]}{\eta_{pS}} \qquad (16)$$

Where ηS_p is the pump efficiency, Q_{pS} is the pump rated flow rate of the source water pump expressed in m^3/s, H_{pS} is the rated the source water pumping head expressed in m and H_{pS1} is the major head losses of the source water pump expressed in m, then;

$$Q_{pS} = \left(\frac{Q_{gdy}}{(60)(60)(SH)}\right)(W_{TP}) \qquad (17)$$

Where W_{TP} is the source water top up fraction (that is the fraction of the total water pumped in day that must come from the water source and not from the lower reservoir, SH denotes the mean sun hours per day which invariably indicates the number of hours which the solar power will use to power the pump per day.

The head losses (H_{pS1}) is computed by using the Darcy-Weisbach head loss equation given as;

$$H_{pS1} = \frac{(f_{dm})(H_{pS})(V_p{}^2)}{2(g)(d_p)} \qquad (18)$$

Where; f_{dm} is used to indicate the Darcy-Weisbach friction factor, H_{pS} is used to indicate the rated pumping head (m), d_{pS} is used to indicate the pipe diameter (m) and V_{pS} is used to indicate the fluid velocity in the pumping pipe (m/s) , then;

$$V_{pS} = \frac{Q_{pS}}{A_{pS}} = \frac{Q_{pS}}{\left(\frac{\pi d_{pS}^{2}}{4}\right)} \qquad (19)$$

Then;

$$f_{dm} = 0.25\left\{\log\left(\frac{\epsilon/d_{pS}}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right\}^{-2} \qquad (20)$$

Where ϵ is used to indicate the pipe roughness, Re is used to indicate the Reynold number where,

$$Re = \frac{(V_{pS})(d_{pS})}{\upsilon} \qquad (21)$$

Where υ is used to indicate kinematic viscosity of water at 25 ^{o}C.

Let $\mathrm{N_{pllpS}}$ be used to indicate the number of parallel pumps used to pump the top up water from the source to the upper reservoir, $Q_{p\mathrm{N_{pllpS}}}$ be used to indicate the flow rate of each of the $\mathrm{N_{pllpS}}$ pumps, then;

$$Q_{p\mathrm{N_{pllpS}}} = \frac{Q_{pS}}{\mathrm{N_{pllpS}}} \qquad (23)$$

Therefore, based on the multiple pumps to be used, power rating of each of the pump which is represented as P_{pllpS} is given as;

$$P_{pllpS} = \frac{(997)(9.81)\left(Q_{p\mathrm{N_{pllpS}}}\right)[H_{pS} + H_{pS1}]}{\eta_{pS}} \qquad (24)$$

Therefore, the sizing of PV is done for the source water top up and also for the regular pumping of water from the lower reservoir to the upper reservoir.

2.4.5. Determination of the Number of PV Module Required for the Water Pumps

The PV panel is used in powering the $\mathrm{N_{pllp}}$ water pumps each for SH sun hours each day with each of the pumps rated as P_{pllp} KW, then, the pumps required energy per day, represented as Epmpdy is defined as;

$$\mathrm{Epmpdy} = (\mathrm{N_{pllp}})(P_{pllp})(\mathrm{SH}) \qquad (25)$$

The PV panel is used in powering the $\mathrm{N_{pllpS}}$ source water top up pumps for SH sun hours each day with each of the pumps rated as P_{pllpS}, then, the source water top up pumps required energy per day, represented as EpmpSdy is defined as;

$$\mathrm{E_{Spmpdy}} = (\mathrm{N_{pllpS}})(P_{pllpS})(\mathrm{SH}) \qquad (26)$$

Let the total energy demand from the two set of pumps be denoted as $\mathrm{E_{Tpmpdy}}$ where;

$$\mathrm{E_{Tpmpdy}} = \mathrm{Epmpdy} + \mathrm{E_{Spmpdy}} \qquad (27)$$

Let W_{PvArr} be the PV array rated power, PSH be the annual mean of daily peak sun hours in kwh/ m^2, η_{inv} be the efficiency of the inverter and it is 90%, η_{cabl} be the cable efficiency which is 90%, $\mathrm{f_{dirt}}$ be the dirt de-rating factor and it is 90%, $\mathrm{f_{temp}}$ be the cell temperature de-rating factor where the cell temperature is denoted as $\mathrm{t_{cell}}$, then (Kyari, Muhammad, Gele, Waziri And Muhammad, 2020);

$$W_{PvArr} = \frac{\mathrm{E_{Tpmpdy}}}{[(\eta_{\mathrm{inv}})(\eta_{\mathrm{cabl}})(\mathrm{f_{temp}})(\mathrm{f_{dirt}})](\mathrm{PSH})} \qquad (28)$$

$$\mathrm{f_{temp}} = 1 - [\gamma(\mathrm{t_{cell}} - \mathrm{t_{STC}})] \qquad (29)$$

$$\mathrm{t_{cell}} = \mathrm{t_a} + 25 \qquad (30)$$

$t_{STC} = 25°C$ (31)

Where t_a denotes ambient temperature expressed in °C , t_{STC} denotes standard test condition temperature expressed in °C and γ denotes the PV Module power temperature coefficient.

Let Wpv denote PV module power rating in watts for each, Vsys denote dc line voltage of the system, Vpv denote the PV module terminal voltage, Npvtl denote total number of PV modules that make up the PV array,. NpvS denote number of PV modules in series and Npvp denote number of PV modules in parallel, then;

$$\text{NpvS} = \frac{\text{Vsys}}{\text{Vpv}} \quad (32)$$

$$\text{Npvtl} = \left(\frac{W_{PvArr}}{\text{Wpv}}\right)1000 \quad (33)$$

$$\text{NpvP} = \frac{\text{Npvtl}}{\text{NpvS}} \quad (34)$$

The total energy yield of the PV array per day, Epvpdy is computed as;

$$\text{Epvpdy} = (W_{PvArr})(\text{PSH}) \quad (35)$$

The solar power efficiency, ηpvsys is computed as;

$$\text{ηpvsys} = \frac{\text{E}_{\text{Tpmpdy}}}{\text{Epvpdy}} \quad (36)$$

The hydro power efficiency, ηhydsys is computed as;

$$\text{ηhydsys} = \frac{\text{Edpdy}}{\text{E}_{\text{Tpmpdy}}} \quad (37)$$

The overall efficiency of the solar hydro power, ηpvhydsys is computed as;

$$\text{ηpvhydsys} = \frac{\text{Edpdy}}{\text{Epvpdy}} \quad (38)$$

2.4.6. Sizing of the inverter

The inverter power denoted as P_{inv} is given in terms the inductive load P_{ind} and resistive load P_{res} as follows (Daniel, Obot, Azuoko, Negedu and Amah, 2020; Olawale And Kayode, 2021);

$$P_{inv} = 1.25\ (P_{res} + 3.5(P_{ind}) \quad (39)$$

Where 1.25 is to account for safety factor and 3.5 is to account for the surge current at the start of the inductive load. Since the water pumps are entirely inductive load, then $P_{res} = 0$ and then;

$$P_{ind} = (\text{N}_{\text{pllp}})(P_{pllp}) \quad (40)$$

$$P_{indS} = (\text{N}_{\text{pllpS}})(P_{pllpS}) \quad (41)$$

Where P_{ind} is for the pumps from the lower reservoir to the upper reservoir while P_{indS} is for the pumps from the top up water source to the upper reservoir.

$$P_{inv} = 4.375(P_{ind}) \quad (42)$$

$$P_{invS} = 4.375(P_{indS}) \quad (43)$$

So, for each pump, the inverter size is;

$$P_{invEach} = 4.375(P_{pllp}) \quad (44)$$

$P_{invSEach} = 4.375(P_{pllpS})$ (45)

3. Results and discussion

Results of the baseline case where the design is based on the actual solar radiation data

The results for the baseline case, where the design is based on the actual solar radiation data is presented in Table 6 for the hydro power and top up water segment and Table 7 for the solar power segment. In Table, 6, the dsign ia for a 600 kW load drawing 24 hours daily energy of 14,400 kWh. The water storage capacity of m^3 is required for the 3 days of power sutonomy. About 50 water pumps each reated at 59.797 kW (approximately 60 kW) are used for the water pump while 10 water pumps each reated at 2989.827 kW (approximately3 kW) are used for the top up water segment. The hydro power with water top up has effiecncy of 0.623 (or 62.3%) and requires 23111.570 kWh of energy every day from the solar power system.

Table 6 The results for the baseline case, for the hydro power and top up water segment.

S/N	Description of parameter	Unit	Value
SUMMARY OF THE HYRDO POWER SEGMENT			
1	Power demand of the load	kW	600
2	Number of hours of power supply per day	hours	24
3	Daily energy demand used to size the hydro turbine and water reservoir	KWh/day	14400
4	Hydro turbine water flow rate	m^3/s	1.632
5	Days of power autonomy	days	3.00
6	Water storage thank (reservoir) capacity	m^3	507,475.97
7	Reservoir water head	m	40
8	Daily pumping hours per day	hours	7.028
9	Total water pump flow rate	m^3/s	6.686
10	Number of parallel water pumps		50
11	Water flow rate of each of the pumps	m^3/s	0.134
12	Power rating of each of the pumps	kW	59.797
13	Total power rating of the pumps	kW	2989.827
14	Daily energy demand of the pumps within the stated hours of water pumping operation per day	kWh	21012.250
SUMMARY OF THE TOP UP WATER PUMP SEGMENT			
15	Top up water pump head	m	42
16	Daily pumping hours per day	hours	7.028
17	Total top up water pump flow rate	m^3/s	0.669
18	Number of parallel water pumps		10
19	Water flow rate of each of the pumps	m^3/s	0.067
20	Power rating of each of the pumps	kW	29.871
21	Total power rating of the pumps	kW	298.712
22	Daily energy demand of the pumps within the stated hours of water pumping operation per day	kWh	2099.320
SUMMARY OF THE ENERGY DEMAND FROM THE HYDRO POWER AND TOP UP WATER PUMP SEGMENT			

23	Operating power required for each identical water pump	kW	59.797
24	Energy demand per day by water pump	kWh	21012.250
25	Energy demand per day by water pump for the top up water	kWh	2099.320
26	Total energy demand per day by all the water pumps	kWh	23111.570
27	The hydro power efficiency	%	0.623

As shown in Table 7, the solar power is designed with the mean solar radiation value of 6.16534 which is obtained by taking the average of the annual mean solar radiation from 2003 to 2023. This is the baseline mean solar radiation. The solar power has daily energy demand of 23,111.57 kWh which is the energy demand from the hydro power segment. The PV power rating is 5,174.29 kW. With 200 Wp PV module, a total of 25,871.46 PV modules are required to supply the needed power. The results showed that the daily energy yield of the PV array is 31,901.29 kWh and the operating efficiency of the PV system is 0.72447 (or 72.4%).

Table 7 The results for the baseline case for the solar power segment

s/n	**description of parameter**	**unit**	**value for the baseline case**
SUMMARY OF THE SOLAR POWER SEGMENT			
1	Daily energy demand from the hydro power and top up water pump segment	kWh	23,111.57
2	Peak sun hour	hours	6.16534
3	Total power rating of the PV array	kW	5,174.29
4	Power rating of each of the PV module	wp	200
5	Voltage rating of each of the PV module	V	12
6	Number of PV module in the array		25,871.46
7	Energy yield per day	kWh	31,901.29
SUMMARY OF THE SYSTEM EFFICIENCY			
8	The solar power efficiency	%	0.72447
9	The hydro power efficiency	%	0.62306
10	The overall power system efficiency	%	0.45139

4. Conclusion

Analytical models for the determination of a solar-hydro power components sizes and the sizes of the pumped water storage reservoirs is presented. Also the detailed statistical analysis of the meteorological dataset used for the analysis is presented. The solar-hydro power is designed with water top-up mechanism to replenish the water lost through evaporation and other mechanisms. The designed solar-hydro power can get its water source from water tanks and this water is recycled. As such, it is easy to sustain the solar-high-power system since the water source can be a fixed size surface water tank. The ideas presented in this are useful for the design of modern solar hydro power plants that can be installed and sustained even in areas with water shortages.

Compliance with ethical standards

No conflict of interest to be disclosed. -

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