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Design and Performance Analysis of 500KVA Pumped-Water-Energy Storage Solar Integrated Power Plant

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Abstract: *In this paper, design and performance analysis of 500 KVA pumped-water-energy storage solar integrated power plants is presented. Akwa Ibom State University, main campus is chosen as the case study site in order to proffer innovative design to improve the current poor power supply in the University. Akwa Ibom State University Main Campus is characterised with geo-coordinates of 4.621437 latitude and 7.763922 longitude, daily mean sunshine hours of 7.13 hours, mean ambient temperature of 26.74 °C and an annual mean solar radiation of 6.22 kW-hr/m^2/day. The case study is a 24 hours per day power supply system with daily energy demand of 9,600.0 KWh/day which requires hydro turbine with water flow rate of 1.45 m^3/s and pumped water storage reservoir capacity of 413,498.94 m^3 to accommodate 3 days of power autonomy. With reservoir water head of 30 m and 7.13 hours of pumping water per day, 40 parallel pumps are required each having a flow rate of 0.1342m^3/s and power rating of 47.638 KW. With solar radiation of 6.22 peak sun hours per day it requires a total of 11,458 PV modules, each rated at 300W to form a 3,437.528 KW PV array to power the pumps. Also, a total inverter size of 10,421KVA is required, split into 40 units of 260.521KVA inverter, one for each of the 40 water pumps. The efficiency of the solar power segment alone is 63.5%, the efficiency of the hydro power segment alone is 70.7% while the combined efficiency of the solar hydro plant is 44.9%. In all, careful combination of* direct supply and pumped water storage is needed to optimize the system efficiency.

Keywords: *Energy Efficiency, Hydro Power, Power Plant, Solar Photovoltaic, Water Pumped.*

1. INTRODUCTION

Over the years, across Nigeria, there has been a rising demand for alternative power supply to address the epileptic power from the national grid [1, 2]. Reliable power supply is very important in a University community for laboratories, workshop operations, information and multimedia communication systems [3,4,5,6,7,8] for effective lectures delivery. Unfortunately, the rising cost of fossil fuels and the need for clean energy system has prompted a sharp rise in adoption of solar power systems as the preferred alternative power source [9,10]. However, due to the unstable nature of solar radiation [11], there is need for power storage units to guarantee steady power supply despite the stochastic nature of solar radiation [12]. In this work, battery power bank and pumped water storage have been the two options that have attracted the attention of researchers in Nigeria [13,14].

Notably, the battery storage option has been widely studied and it is easy to setup. However, the short lifespan of battery and the high cost of battery units make it more expensive. Accordingly, this work examines the pumped water storage option whereby the solar power system is used to generate energy which can be used to directly power the load and at the same time excess energy can pump water to an upper reservoir where the water will be used on a hydro power turbine to generate electric power. The concept has been presented in [14] but the study did not accurately determine the water pump as the electrical load to the solar power system. In that case, the design calculations presented in [14] are only suitable for directly supplying the energy from the solar power to the load. In this work, the error has been addressed and the system performance determined; on standalone because, the performance of the solar power segment, the efficiency of the hydro power segment and the combined solar hydro power plant efficiency have been determined. Essentially, this work presented requisite procedure and design calculations for sizing the solar hydro power plant and for evaluating the system performance in terms of efficiency.

2. METHODOLOGY

2.1 The System Model and Meteorological Data

The power system presented in this work is innovative solar hydro power plant where the solar energy is used to generate the energy via the photovoltaic (PV) array [15] (as shown in Figure 1). Then, in one configuration, the energy generated from the solar power is used to pump water to a reservoir which is used to drive the hydro power turbine generating the electrical energy that is finally delivered to the load. In another configuration, the solar generated power can be used to drive the load directly. The essence of the pumped water storage is to facilitate the energy storage such that the solar energy generated can be used even when the solar radiation is not available or inadequate to drive the load.

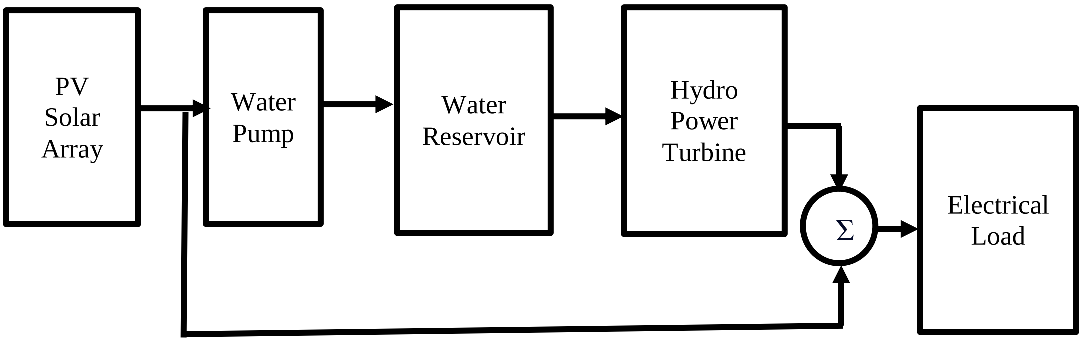

Figure 1: Block diagram of system architecture

Specifically, this work focuses on the design of 500KVA pumped water energy storage solar integrated power plant for Akwa Ibom State University (Main Campus) with geo-coordinates of 4.621437 latitude and 7.763922 longitude (as shown in Figure 2). Akwa Ibom State University, main campus was chosen as the case study site in order to proffer innovative design as an alternative power source to improve the current poor power supply to the University. The system design requires determination of the daily energy (load) demand, sizing of the water reservoir and water pump components including the photovoltaic solar power components. Furthermore, the design requires some meteorological data of the installation site. Particularly, the mean daily sunshine hours is needed to determine the mean water pumping hours per day, the ambient temperature is needed to determine the cell temperature of the photovoltaic (PV) module, while the peak sun hour or solar radiation data is needed to determine the required PV power and number of PV modules [16,17].

Figure 2: Akwa Ibom State University (Main Campus) with geo-coordinates of 4.621437; 7.763922

Figure 2, shows the location of the case study site, Akwa Ibom State University, main campus with geo-coordinates of 4.621437 latitude and 7.763922 longitude, located in the South South region of Nigeria. The monthly mean sunshine hour for the site, as extracted from the Global Weather and Climate server [18] is presented in Figure 3. It has maximum sunshine hour of 11.08 in January, minimum sunshine hour of 7.13 hours in August and annual mean sunshine of 9.29 hours as depicted in Figure 3.

Figure 4, presents the monthly mean temperature for the site, as extracted from NASA portal [19]. It has a maximum temperature of 27.79 °C in February, a minimum temperature of 25.71 °C in August and an annual mean temperature of 26.74 °C.

Figure 5, presents the monthly mean of daily peak sun hours for the site, as extracted from NASA portal. It has a maximum of 6.74 kW-hr/m^2/day in October, a minimum of 5.42 kW-hr/m^2/day in December and an annual mean of 6.22 kW-hr/m^2/day.

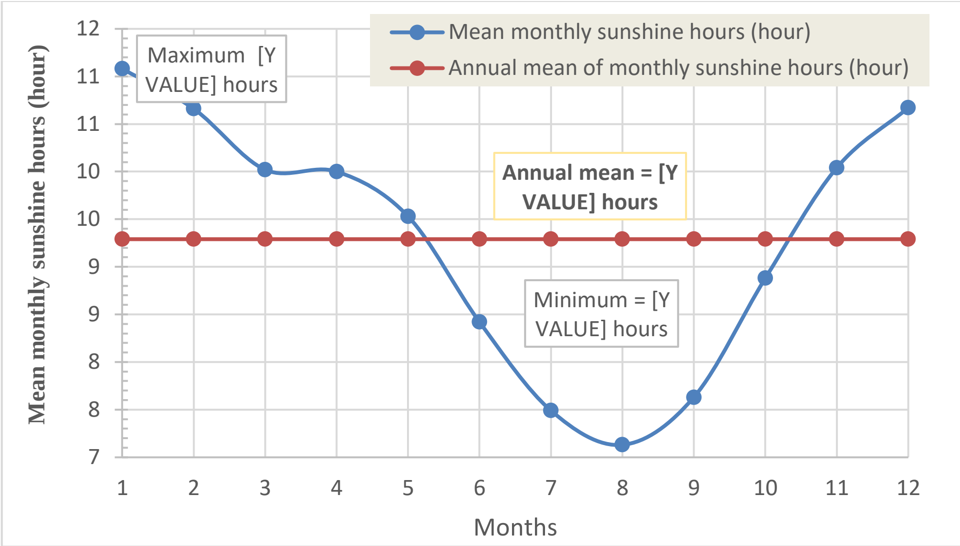

Figure 3: The monthly sunshine hours for Akwa Ibom State University (Main Campus).

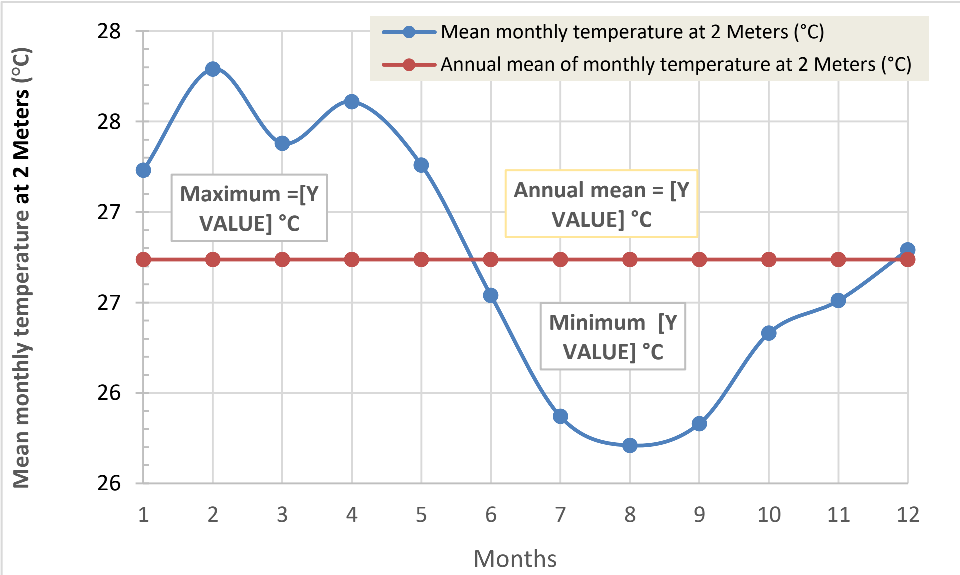

Figure 4: The monthly mean temperature for Akwa Ibom State University (Main Campus)

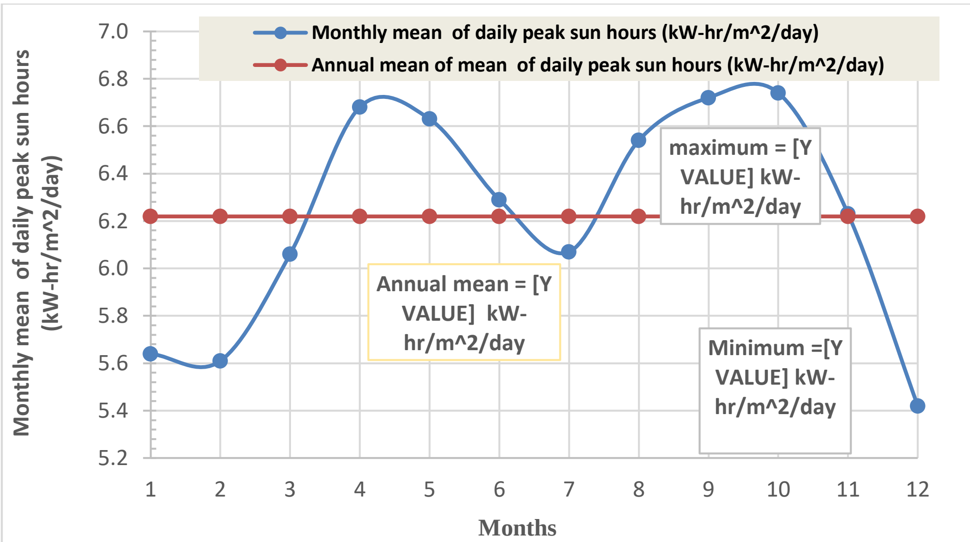

Figure 5: The Monthly mean of daily peak sun hours for Akwa Ibom State University (Main Campus).

2.2 Determination of the Daily Energy Demand

Determination of the daily energy demand, denoted as Edpdy is based on the following parameters: the daily power demand expressed in KW (PrKw), Power factor (pf), power rating in KVA (PrKVA) and hours of operation per day (hpdy). The solar hydro power plant is rated 500 KVA, that means PrKVA = 500 KVA, hence.

$$PrKw = (\text{PrKVA})(pf) \tag{1}$$

Given that pf = 0.8, then, $PrKw = (500)(0.8)$= 400 KW. Also,

$$\text{Edpdy} = (PrKw)(\text{hpdy}) \tag{2}$$

Given that the power plant will supply power for 24 hours per day, that is, hpdy = 24, then, $\text{Edpdy} = (400)(24)$= 9,600.0 KWh/day.

2.3 Sizing of the Hydro Power and Pumped Storage Components

2.3.1 Determination of the generating flow rate and generating pipe diameter

The hydro power turbine is expected to generate the power, $PrKw$. The generator flow rate, denoted as Q_g with unit in m^3/s is given in [13] as;

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

Where, ρ denotes water density at 25 °C which is 997 kg/m^3, η_t denotes the efficiency of the turbine which is 0.93, g denotes acceleration due to gravity which is 9.81 m/s^2 and H_g denotes the rated water head which is 30 m. Then,

$$Q_g = \frac{400}{(997)(9.81)(0.94)(30)} = 1.45\ m^3/\text{s}.$$

If the generating pipe area is denoted as, A (in m^2), V, denotes the velocity of flow in the pipe (in m/s), and d_g denotes the generating pipe diameter given in m, then;

$$A = \frac{\pi {d_g}^2}{4} = \frac{Q_g}{V} \tag{4}$$

Hence,

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

Let the V = 2.2 m/s, then; $d_g = \sqrt{\frac{4(1.45)}{\pi(2.2)}}$ = 0.92m

2.3.2 Determination of the water reservoirs size

Let *daut* denotes days of power autonomy (in days), *fsfrsv* denotes the safety factor for the reservoir storage capacity, Q_{gdy} denotes the daily flow rate per day and the C_{rsv} denotes the capacity of the reservoir (m^3) which is given in terms of 86400 seconds (that is (60 x 60 x 24) per day as follows;

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

$$\text{Crsv} = Q_{gdy}\,(\text{daut}) \tag{7}$$

Hence,, $Q_{gdy} = (86400)(1.45) = 137{,}832.98\ m^3$/day

With *fsfrsv* = 1.1 and also 3 days of power autonomy, daut = 3, then;
Crsv = $(86400)(1.45)(3)$ =$(86400)(1.45)(3)(1.1)$ = 413,498.94 m^3

2.3.3 Determination of the rated pumping flow rate and the water pump power

The pump power (P_{pr}) required to pump water to the elevated reservoir is given in [14] as:

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

Where P_{pr} is in kW, η_p denotes the efficiency of the pump, Q_p denotes the rated flow rate of the pump in m^3/s, H_p denotes the rated pumping head in m while H_{p1} denotes the major head losses in m.

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

Where, *SH* is the mean sun hours per day. It essentially denotes the number of hours the solar energy used to power the pump will be in supply per day. Hence, with *SH* of 7.13 hours, then;

$$Q_p = \frac{137{,}832.98}{(60)(60)(7.13)} = 5.37\ \text{m}^3/\text{s}$$

The head losses (H_{p1}) is determined using Darcy-Weisbach head loss equation as follows;

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

f_{dm} denotes the Darcy-Weisbach friction factor, H_g denotes the rated pumping head (m), d_p denotes the pipe diameter (m) and V_p denotes the fluid velocity in the pumping pipe (m/s) which from Equation 4 is given as;

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

Where d_p is the pipe diameter ($d_p = 0.75\ m$).

$$V_p = \frac{Q_p}{\left(\frac{\pi d_p{}^2}{4}\right)} = \frac{5.37}{\left(\frac{\pi \text{ x } 0.75^2}{4}\right)} = 12.15\ m/s$$

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

Where ϵ denotes the pipe roughness, Re denotes the Reynold number where,

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

Where υ denotes kinematic viscosity of water at 25°C which is $8.917 \text{ x } 10^{-7}$. Then,

$$Re = \frac{12.15 \text{ x } 0.75}{8.917 \text{ x } 10^{-7}} = 1.02 \text{ x} 10^7.$$

Now, ϵ is the steel pipe roughness, $45 \text{ x } 10^{-6}$ m, then;

$$f_{dm} = 0.25\left\{\log\left(\frac{(45 \text{ x } 10^{-6})/(0.75)}{3.7} + \frac{5.74}{(1.02\text{x } 10^7)^{0.9}}\right)\right\}^{-2} = 0.0112$$

Therefore, substituting in Equation 10,

$$H_{p1} = \frac{(0.0112)(30)((12.15)^2)}{2(9.81)(0.75)} = 3.38$$

Let N_{pllp} denotes the number of parallel pumps used, $Q_{pN_{pllp}}$ denotes the flow rate of each of the N_{pllp} pumps where;

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

If $N_{pllp} = 40$, then;

$$Q_{pN_{pllp}} = \frac{5.37 \text{ m3/s}}{40} = 0.1342 \text{ m3/s}$$

Therefore, the power rating of each of the pumps is denoted as P_{pllp} which is given from Equation 8 as follows;

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

Hence, with $\eta_p = 0.9$, then;

$$P_{pllp} = \frac{997 \text{ x } 9.81 \text{ x } 0.1342\ [30 + 7.65]}{0.92} = 47.638 \text{ KW}.$$

So, 40 pumps, each rated 47.638 KW are required to pump the water to the reservoir that has water head of 30m.

2.4 Sizing of the Photovoltaic Solar Power Components

2.4.1 Determination of the number of PV module required for the water pumps

The solar power is used to power the N_{pllp} water pumps for SH sun hours per day where each of the pumps [20,21] is rated P_{pllp} KW, hence, the energy required by the pump per day, denoted as Epmpdy is given as;

$$\text{Epmpdy} = (N_{pllp})(P_{pllp})(\text{SH}) \quad (16)$$

Given that SH = 7.13 hours, hence, Epmpdy = $(40)(47.638)(7.13)$ = 13,586.430 KWh per day.

Let W_{PvArr} denotes the power rating of the PV array, PSH denotes the yearly mean of daily peak sun hours in kwh/ m^2, η_{inv} presents the inverter efficiency which is taken as 90%, η_{cabl} expresses the cable or connection (loss) efficiency which is taken as 90%, f_{dirt} denote the de-rating factor due to dirt and it is taken as 90%, f_{temp} gives the de-rating factor due to cell temperature denoted as t_{cell}, where [22];

$$W_{PvArr} = \frac{\text{Epmpdy}}{[(\eta_{inv})(\eta_{cabl})(f_{temp})(f_{dirt})](\text{PSH})} \quad (17)$$

$$f_{temp} = 1 - [\gamma(t_{cell} - t_{STC})] \quad (18)$$

$$t_{cell} = t_a + 25 \quad (19)$$

$$t_{STC} = 25°\text{C} \quad (20)$$

Where t_a is the ambient temperature in °C , t_{STC} is the standard test condition temperature in °C and γ is the power temperature coefficient of the PV Module. Given that PSH = 6.22, $t_a = 27°C$, $\gamma = 0.48\%/°C$, $\eta_{inv} = 90\%$, $\eta_{cabl} = 90\%$, and $f_{dirt} = 90\%$, then;

$$t_{cell} = 27 + 25 = 52\ °C$$

$$f_{temp} = 1 - [0.48/100(52 - 25)] = 0.872$$

Then,

$$W_{PvArr} = \frac{13{,}586.430}{[(0.9)(0.9)(0.872)(0.9)](6.22)} = 3{,}437.528\ \text{KW}$$

Let *Wpv* be the power rating in watts for each PV module, *Vsys* be the system line dc voltage, *Vpv* be the terminal voltage of each PV module, *NpvS* be the number of PV modules connected in series, *Npvp* be the number of PV modules connected in parallel and *Npvtl* be the total number of PV modules in the PV array.

$$\text{NpvS} = \frac{\text{Vsys}}{\text{Vpv}} \quad (21)$$

$$\text{Npvtl} = \left(\frac{W_{PvArr}}{\text{Wpv}}\right)1000 \quad (22)$$

$$\text{NpvP} = \frac{\text{Npvtl}}{\text{NpvS}} \quad (23)$$

Hence, given that V*sys* = 120V, *Vpv* = 12V, *Wpv* = 300W, then;

$$\text{NpvS} = \frac{120}{12} = 10$$

$$\text{Npvtl} = \left(\frac{3{,}437.528}{300}\right)1000 = 11{,}458$$

$$\text{NpvP} = \frac{11{,}458}{10} = 1{,}146$$

Total PV energy yield per day, Epvpdy is given as;

$$\text{Epvpdy} = (W_{PvArr})(\text{PSH}) \quad (24)$$

Hence,

$$\text{Epvpdy} = (3{,}437.528)\ (6.22) = 21{,}381\ \text{kWh per day}$$

Efficiency of the solar power segment, ɳpvsys is given as;

$$\eta\text{pvsys} = \frac{\text{Epmpdy}}{\text{Epvpdy}} \quad (25)$$

Hence,

$$\eta\text{pvsys} = \frac{13{,}586.430}{21{,}381} = 0.635 = 63.5\%$$

Efficiency of the hydro power segment, ɳhydsys is given as;

$$\eta\text{hydsys} = \frac{\text{Edpdy}}{\text{Epmpdy}} \quad (26)$$

Hence,

$$\eta\text{hydsys} = \frac{9{,}600.0}{13{,}586.430} = 0.707 = 70.7\ \%$$

Efficiency of the combined solar hydro power segment, ɳpvhydsys is given as;

$$\eta\text{pvhydsys} = \frac{\text{Edpdy}}{\text{Epvpdy}} \quad (27)$$

Hence,

$$\eta\text{pvhydsys} = \frac{9{,}600.0}{21{,}381} = 0.449 = 44.9\%$$

2.4.2 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 [23,24,25];

$$P_{inv} = 1.25\ (P_{res} + 3.5(P_{ind}) \quad (28)$$

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

$$P_{ind} = (\text{N}_{\text{pllp}})(P_{pllp}) \quad (29)$$

Where N_{pllp}, denotes the number of parallel pumps used and P_{pllp} is the power rating of each of the pumps. Hence,

$$P_{ind} = (\mathrm{N_{pllp}})(P_{pllp}) = (40)(47.638) = 1905.52\ KW,$$

Then;

$$P_{inv} = 1.25\ (0 + 3.5(1905.52) = 8{,}337\ \mathrm{KW}$$

In KVA, the inverter power P_{invKVA} is given as;

$$P_{invKVA} = \frac{P_{ind}}{pf} \tag{30}$$

Hence,

$$P_{invKVA} = \frac{8{,}337}{0.8} = 10{,}421\ \ \mathrm{KVA}$$

Since there are 40 water pumps, the inverter size for each of the water pumps is given;

$$\frac{P_{invKVA}}{40} = 260.5217\ \mathrm{KVA}.$$

Thus, about 40 units of 260.5217 KVA inverters will be required.

3. RESULTS AND DISCUSSUION

The detailed design calculations for a case study 500 KVA pumped water storage solar hydro power plant for Akwa Ibom State University (Main Campus) with geo-coordinates of 4.621437; 7.763922 is presented. The daily mean sunshine hours of 7.13, mean ambient temperature of 26.74 °C and an annual mean of daily solar radiation of 6.22 kW-hr/m^2/day were used in the design calculations. The power plant will supply 500 KVA power for 24 hours per day, and this gives daily energy demand of 9,600.0 KWh/day. The per second water flow rate for the hydro turbine is 1.45 m^3/s, the daily water flow rate is 137,832.98 m^3/day which requires a reservoir capacity of 413,498.94 m^3 to accommodate 3 days of power autonomy from the stored pumped water in the reservoir. The reservoir water head is 30 m and with the 7.13 hours of pumping water per day, a flow rate of 5.37 m^3/s is required for pumping the water to the reservoir. Eventually, 40 parallel pumps were required each having a flow rate of 0.1342 m3/s and power rating of 47.638 KW.

The 40 water pumps serve load to the PV power system which gives rise to a daily energy demand of 13,586.430 KWh per day require PV array rated at 3,437.528 KW with solar radiation of 6.22 peak sun hours per day to power the pumps. Overall, a total of 11,458 PV modules, each rated at 300 watts are required to form the PV array. A total inverter size of 10,421 KVA is required for spliting into 40 units of 260.5217 KVA inverter, one for each of the 40 water pumps.

The efficiency of the solar power segment alone is 63.5%, the efficiency of the hydro power segment alone is 70.7 % while the combined efficiency of the solar hydro plant is 44.9%. This means that direct supply of energy from the solar to the 500 KVA load would have saved 18.64% of the energy, the need for storage is essential since the solar power is not stable and can only be available for some hours in a day. Consequently, careful combination of direct supply and pumped water storage is needed to optimize the system efficiency.

4. CONCLUSION

In this study, the design procedure and calculations for sizing of a solar hydro power plant is presented. The system utilizes solar power to pump water to upper reservoir which is used to drive the hydro power turbine that delivers the energy to the load. Specifically, the load is 500 KVA power supply to a university campus.

The work used some meteorological data of the power system installation site along with the daily load demand of the campus to determine the components' sizes for the hydro power turbine, the water pump, the reservoir capacity, the PV array size and the inverter size. The study also determined the efficiency of the solar power segment alone, the hydro power segment and the combined efficiency of the solar hydropower system. The results showed that the hydro power segment has slightly higher efficiency than the solar segment. Also, each of the two segments has efficiency that is above 63%. However, the combined system efficiency is less than 50%. This work has demonstrated a critical energy efficiency system and energy management for sustainability with wider potential for scale-up and optimization.

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