Design and Evaluation of Solar–Pumped Storage hybrid Power System for Rural Communities in Nigeria

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Abstract - *This research is part of a project to develop a solar-pumped storage hybrid power system for remote rural communities where there is absent of Runoff River, waterfalls and grid. Proper sizing of the components is important to the success of any model, installation and project. The components selection is the first phase of the project which will look at developing hybrid system requirements. This paper presented method of selecting components of the solar-pump storage hybrid system through mathematical analysis, using the specification of the load to calculate the generator, turbine, pump, inverter, battery bank ratings as well as the size of the overhead and underground tanks. The pump is designed to consistently pump water to the overhead tank to ensure a continuous supply of electricity. The results of the design shows that it is a feasible way of generating electricity from sun and water where there is no run off river and water fall.*

***Key Words*: Solar energy system, hydro energy system, pump storage, hybrid.**

1. INTRODUCTION

Access to electrical energy promotes economic growth and improve the standard of living of the people. Electrical energy can be produced from fossil fuels or renewable energy resources. Different location have different sources of electrical energy. In Nigeria, electrical energy is mostly sourced from hydropower, fossil fuels such as diesel, petrol, etc. and grids are used to transmit and distribute the energy in urban areas, cities, towns and some rural areas. This energy is used in different sectors such as in health care sector, communication system, constructions, education etc. for different purposes to improve the economy and standard of living. About 59% of the population of Nigeria lives in rural areas where there is absent of electricity grid. These rural areas resort to the use of firewood for cooking and lighting, candles, torch light, lantern for lighting, small petrol and diesel engine generator to provide electricity. Petrol and diesel engine generators are costly to operate and maintain, they are unreliable and economically not sustainable. In addition, they emit greenhouse gasses, which are harmful to the environment and cause global warming. Lack of access to electricity results to increased poverty, poor health care, poor communication system etc. in remote rural areas. More worrisome is the state of health facilities in the remote rural areas. Government have provided health facilities in some of these rural communities, some of the health facilities are abandoned and some are operating skeletal services. There is poor health services, increase in mortality rate etc. all because of inability to buy diesel, petrol to provide electricity for some basic medical equipment. Many doctors refuse to stay in rural areas and are migrating to the cities because of lack of basic amenities resulting from lack of electricity.

In some of these remote rural communities, there is abundance renewable energy potential such as run-off river, solar, biomass, wind energy that can be utilise to produce electricity. These sources of energy can be used with fossil fuels as standalone hybrid system or integrate to electricity grid to provide reliable electricity [1][2]. Renewable energy sources have zero greenhouse gas emission, they have low cost of operation as there is absence of fuel cost, they are inexhaustible, can be used close to the source and in remote areas where there is no grid. They reduce or eliminate the cost of grid extension and are environmentally friendly.

Many researchers and developers of renewable energy resources have studied, proposed and even installed hybrid system involving Solar photovoltaic (PV)/Wind; Solar PV/ wind/diesel; and Solar PV/wind/micro hydro, for different communities and use. B.U Musa et al. modelled and analyzed PV/wind hybrid with storage for small community [3][4]. Design and optimization of hybrid system e.g. Solar PV/biomass, PV/Wind energy hybrid is widely carried out using HOMER [5][6]. Different location require different hybrid system due to different weather and climatic conditions such as solar radiation, temperature, run-off river flow rate, water heads etc. For hybrid system to be successful, two or more energy sources must be available at the same location e.g. sun and wind; sun, wind and hydro; sun, wind, hydro; and storage batteries. Most proposal of hybrid system with hydro considers Run-off Rivers, water falls or construction of artificial dam. However, there are many rural areas with abundant solar radiation suitable for electricity generation but no Run-off River nor water falls. In such a location, a solar PV/hydro hybrid system is possible with the use of pumped storage [7]. In order take efficient and economic use of solar and pumped storage hybrid system, sustainable, reliable design and proper component sizing and selection is required. This paper present the design and evaluation of a solar-pumped storage hybrid power system for rural communities in Nigeria. This is to ensure a reliable supply of electricity to meet the load demand in rural communities and provide a reliable electricity to their clinic or general hospital.

2. SOLAR-PUMPED STORAGE HYBRID SYSTEM

Electrical loads can be supplied with only solar PV system or only hydro energy source. When solar is only used, the solar power is not available to supply the load demand for all the hours of the day. Power is only available when there is sunshine with adequate solar radiation. These happens at certain period of the day and left the remaining part of the day without supply. Batteries are then added to provide storage during the period of sunshine and used to provide continuous power supply even in the night when the sun is off. In order to further enhance reliability of power supply to the load from the hybrid system, hydro energy resources is added to the system. And where there is no run –off river or water falls. The hydro sources is replaced with a pumped storage system. The block diagram of the solar-pumped storage hybrid system is shown in the figure below.

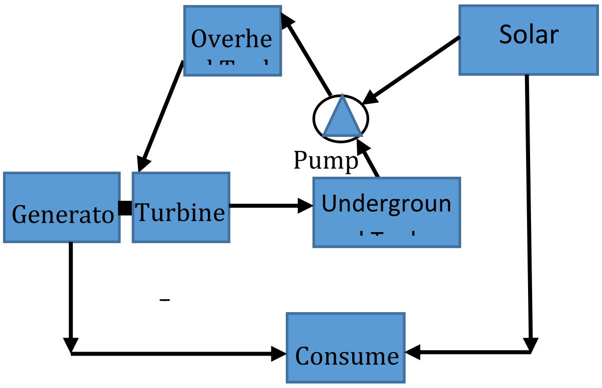


Fig -1: Block diagram of a solar-pumped storage hybrid system

The system has been designed to utilise solar energy and energy of water falling from a height. It consist of an underground water storage tank or a water well, solar PV system, battery bank, inverter, a water pump, overhead water tank, a water turbine and a generator. The water in the underground tank or water well is pumped to the overhead tank using a water pump powered by solar photovoltaic system, inverter and battery bank. The pumped water in the overhead tank falls down at a high speed through a pipe of appropriate diameter to the turbine. The potential energy of the water through the pipe is converted to mechanical energy used to turn the turbine and the generator connected to the turbine converts the mechanical energy to electrical energy. Whenever there is solar, the pump pumps water to the overhead tank and when the sun is off (during cloudy weather and night), the battery bank provide power to the pump for pumping water. The systems is also intended to work in such a way that the excess power produced by the solar PV system is used to pump water from the underground to the overhead tank. Once the overhead tank is filled, water is preserved in the overhead tank while the solar PV system, inverter and battery supply the required power to the load and when the load demand increases, water is released at an elevation from the overhead tank to the turbine to generate electricity. This cycle continue over and over providing a reliable 24hr period power supply to the load without dependence on electricity from the grid. This system is proposed to have an intelligent water pump controller that will start and stop pumping water automatically when the water level is low and high respectively.

2.1. Design Parameters of Solar-Pump Storage Hybrid System

The design of the hybrid system is aimed at knowing the rating and capacity of components and materials to be selected to meet the load demand of a remote rural areas for a 24hr operation. The major factor that determine the size and capacity of components is the electric load. So the first step is to determine the load demand of the community. The electrical loads of a typical rural community consists of lighting bulbs, ceiling fans, refrigerators, water pump, televisions, computers, etc. in addition, some basic medical equipment in clinic, heath facilities or hospital. We are proposing a design for a total daily power demand of 25kW, for a rural remote community with adequate solar radiation. This is in consideration that, the use of air conditioner is excluded, ventilation will only be provided with the ceiling and standing fans. The design of the solar-pumped storage hybrid system is grouped into the following;

2.2. Design of the Overhead Tank

Overhead tank is required to hold adequate capacity of water to flow consistently to the hydro turbine. Therefore, there is need to know parameters such as size of the overhead tank, the tank area, volume and the flow rate of water from the overhead tank to the turbine. The overhead tank must have the require diameter and area to contain enough volume of water which will pass through the pipe between the overhead tank and the turbine to provide enough potential energy of water falling through a high level (head) to spin the turbine. The head and the flow of water determines the amount of power and energy that can be generated. The more the head, the more water pressure the turbine will receive and the more power and energy it will produce. The potential energy at which water falls is given by;

$$P.E = M\ x\ g\ x\ H\ (J) \qquad 1$$

Where M, is the mass of water, (kg), g is the gravitational force = $9.81m^2$ and H is the net head (m) which is the height to which the pump can raise water to the overhead tank. The mass of water is given by;

$$M = \rho\ x\ V_{OT}\ (kg) \qquad 2$$

Where, ρ the water density given as $1000kg/m^2$, V_{OT} is the overhead tank volume in liters given as;

$$V_{OT} = A_{OT} \; x \; h \; x \; 1000 \qquad 3$$

Where, h is height of the overhead tank and the tank area, A_{OT} is given as;

$$A_{OT} = \frac{\pi}{4} {D_{OT}}^2 \qquad 4$$

Where, D_{OT} is the diameter of the overhead tank.

The water in the overhead tank will have to flow to the turbine through a pipe at a required flow rate. The flow rate, Q_{OP} can be calculated using;

$$Q_{OP} = A_{OP} \, \text{x} \, V_{OP} \; (m^3/s) \qquad 5$$

Where, A_{OP} is the area of the pipe between the overhead tank and turbine and V_{OP} is the velocity of water flowing through the pipe given by;

$$A_{OP} = \frac{\pi}{4} {D_{OP}}^2 \qquad 6$$

$$V_{OP} = (2 \times g \times H)^{\frac{1}{2}} \qquad 7$$

Where, D_{OP} is the diameter of the pipe between the overhead tank and the turbine.

2.3. Design of the Turbine

The turbine converts the potential energy of falling water to mechanical energy. Therefore the mechanical power of the turbine, $P_{turb.}$ and the angular velocity of the turbine ω are given by;

$$P_{turb.} = T \; x \; \omega \; \text{(W)} \qquad 8$$

$$\omega = \frac{2\pi N}{60} \; \text{(rad/sec)} \qquad 9$$

Where, T is the torque (Nm), N is the rotational speed (rpm). The rotational speed of the turbine depends on the type of turbine used. The turbine use is a low head turbine such as Kaplan and Francis turbine or Pelton wheel [8][9]. The rotational speed for Kaplan and Francis turbine is given as;

$$N = K \times H^{-0.5} \; \text{(rpm)} \qquad 10$$

Where, for Kaplan, $K = 800$ and for Francis, $K = 600$

On the other hand, Pelton wheel rotational speed is given by;

$$N = 31 \times \left(\frac{H \times Q}{j}\right)^{0.5} \; \text{(rpm)} \qquad 11$$

And the runner throat diameter of the turbine is given by;

$$D = K \times Q^{-0.473} \; \text{(rpm)} \qquad 12$$

Once the rotational speed of the turbine is known, a generator of equal speed and frequency (usually 50Hz) or with a speed close to that of the turbine is selected to enable synchronism. The synchronous speed N_S and the number of poles P of the generator are given as;

$$N_S = \frac{120f}{P} \qquad 13$$

$$P = \frac{120f}{N_S} \qquad 14$$

2.4. Design of the Underground Water Tank

The pump is expected to pump water from the underground water tank through a pipe of appropriate diameter and area to the overhead tank. The power demand of the pump, P_{pump} to carry this out can be found using;

$$P_{pump} = \frac{\rho \times g \times Q_{UT} \times H}{1000 \; x \, \eta} \; \text{(kW)} \qquad 15$$

$$Q_{UT} = A_{UT} \, \text{x} \, V_{UT} \; (m^3/s) \qquad 16$$

η, Q_{UT} and H, are obtained from the characteristics of the pump at an operating point [10][11]. Where, η is the efficiency of the pump, A_{UT} is the area of the pipe between the overhead tank and pump, Q_{UT} is the flow rate of water through the pipe and V_{UT} is the velocity of water flowing through the pipe is given by;

$$A_{UT} = \frac{\pi}{4} {D_{UT}}^2 \qquad 17$$

It is required of the water pump to have enough power to pump water continuously to the overhead tank. The water pump power is used to know the amount of water pumped to the overhead tank which balances the amount of water flowing into the turbine at the specified flow rate and is calculated by using Bernoulli equation [12] given by;

$$P_1 + \frac{\rho {v_1}^2}{2} + \Delta P_{Pump} + \rho g_{z_1} = P_2 + \frac{\rho {v_2}^2}{2} + \Delta P_{loss} + \rho g_{z_2} \qquad 18$$

$$\Delta P_{Pump} = (Z_2 - Z_1) + \Delta P_{loss} \qquad 19$$

$$\Delta P_{loss} = \left(f \frac{\rho v^2}{2} \frac{l_x}{D_x}\right) \qquad 20$$

The following should be considered to determine the velocity of water in the pipes, the atmospheric pressure, $P_1 = P_2 = 0$, the velocity at point 1 and point 2; $V_1 = V_2 = 0$, and equation 18 becomes;

$$f \frac{\rho v^2}{2}\left(\frac{l_1}{D_1} - \frac{l_2}{D_2}\right) - Z_2(1 + \rho g) + Z_1(1 - \rho g) = 0 \qquad 21$$

Where, l_1 and D_1 are the length (m) and diameter (m) of the pipe between the underground tank and the pump, l_2 and D_2 are the length (m) and diameter (m) of the pipe between the pump and the overhead tank, f is the friction factor, Z_1 is the depth of the underground water tank or water well, Z_2 is the elevation from the base of the underground water tank to the overhead water tank and the relative roughness r of material given by;

$$r = \frac{\in}{Dpipe} \qquad 22$$

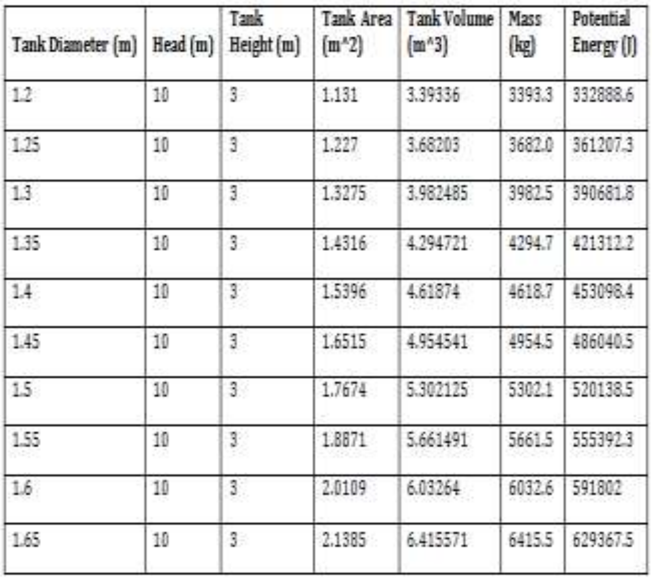
Where, $Dpipe$ is the diameter of pipe (mm).

The friction factor, f is known from the value of the relative roughness; r using the moody diagram [13][14]. Different material have different absolute roughness and their choice depends on the area of application. In this study a commercial steel pipe with absolute roughness $\in = 0.046$ is chosen.

3. RESULTS AND DISCUSSION

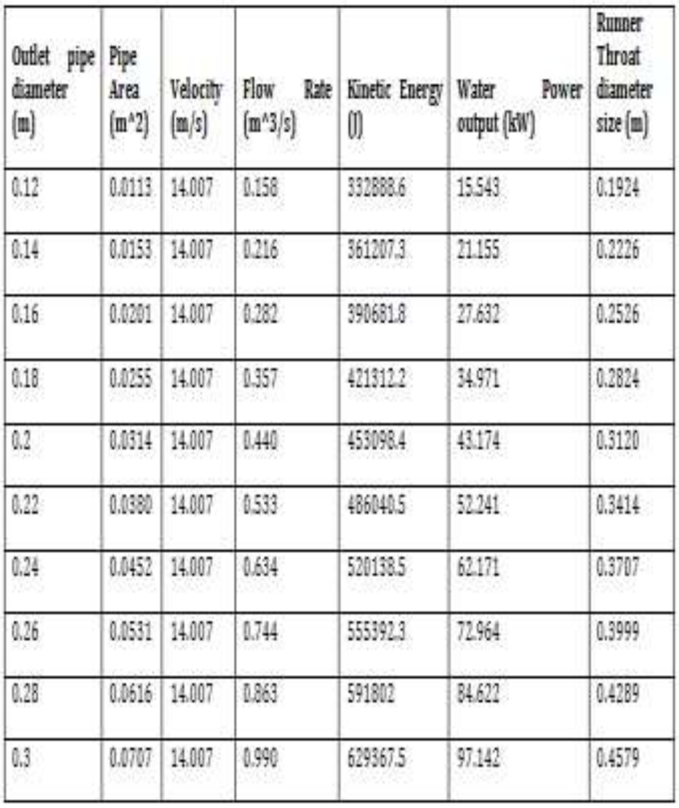
The results of the design calculations are shown in table 1 to table 4. The head of the overhead tank and the tank height were kept at a fixed value and the tank diameter varies. Table 1 shows how the potential energy, kinetic energy, power and tank volume varies as the tank diameter changes. It can be seen that the higher the tank diameter, the more volume of water it will be in the overhead tank and the higher the flow rate. These results have been used in the selection of components and materials for the hybrid system in section 3.1.

Table -1: Volume and potential energy of the overhead tank of height = 3m and head = 10m.



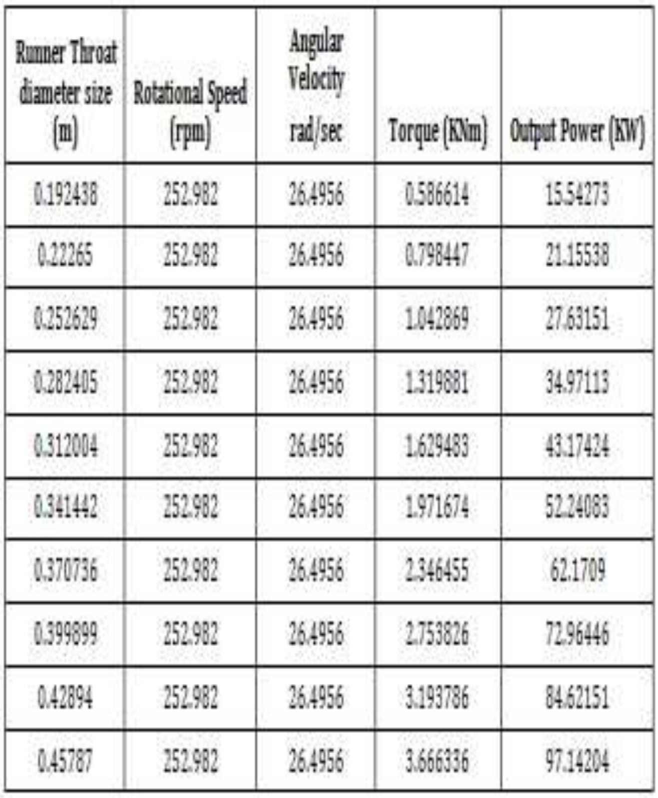
Tank Diameter (m)	Head (m)	Tank Height (m)	Tank Area (m^2)	Tank Volume (m^3)	Mass (kg)	Potential Energy (J)
1.2	10	3	1.131	3.39336	3393.3	332888.6
1.25	10	3	1.227	3.68203	3682.0	361207.3
1.3	10	3	1.3275	3.982485	3982.5	390681.8
1.35	10	3	1.4316	4.294721	4294.7	421312.2
1.4	10	3	1.5396	4.61874	4618.7	453098.4
1.45	10	3	1.6515	4.954541	4954.5	486040.5
1.5	10	3	1.7674	5.302125	5302.1	520138.5
1.55	10	3	1.8871	5.661491	5661.5	555392.3
1.6	10	3	2.0109	6.03264	6032.6	591802
1.65	10	3	2.1385	6.415571	6415.5	629367.5

Table -2: Power and flow rate of water from the overhead tank.



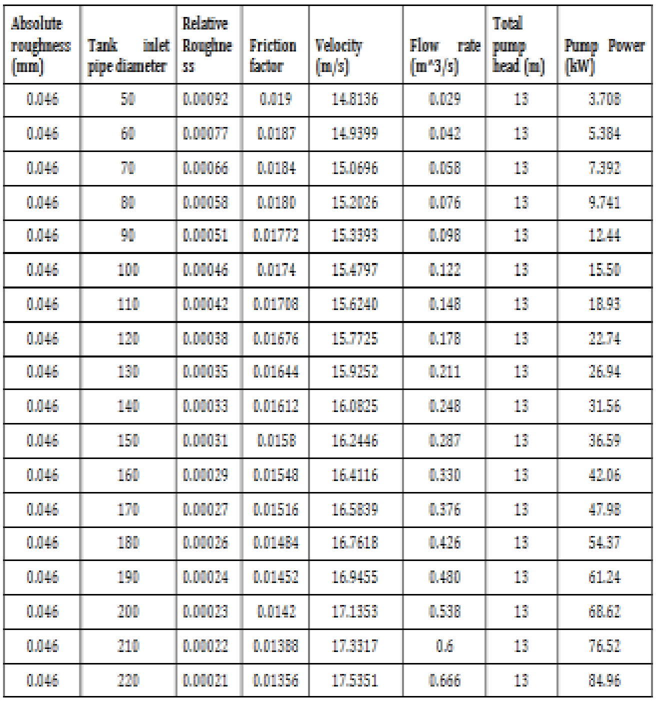
Outlet pipe diameter (m)	Pipe Area (m^2)	Velocity (m/s)	Flow Rate (m^3/s)	Kinetic Energy (J)	Water Power output (kW)	Runner Throat diameter size (m)
0.12	0.0113	14.007	0.158	332888.6	15.543	0.1924
0.14	0.0153	14.007	0.216	361207.3	21.155	0.2226
0.16	0.0201	14.007	0.282	390681.8	27.632	0.2526
0.18	0.0255	14.007	0.357	421312.2	34.971	0.2824
0.2	0.0314	14.007	0.440	453098.4	43.174	0.3120
0.22	0.0380	14.007	0.533	486040.5	52.241	0.3414
0.24	0.0452	14.007	0.634	520138.5	62.171	0.3707
0.26	0.0531	14.007	0.744	555392.3	72.964	0.3999
0.28	0.0616	14.007	0.863	591802	84.622	0.4289
0.3	0.0707	14.007	0.990	629367.5	97.142	0.4579

Table -3: Turbine parameters



Runner Throat diameter size (m)	Rotational Speed (rpm)	Angular Velocity rad/sec	Torque (KNm)	Output Power (KW)
0.192438	252.982	26.4956	0.586614	15.54273
0.22265	252.982	26.4956	0.798447	21.15538
0.252629	252.982	26.4956	1.042869	27.63151
0.282405	252.982	26.4956	1.319881	34.97113
0.312004	252.982	26.4956	1.629483	43.17424
0.341442	252.982	26.4956	1.971674	52.24083
0.370736	252.982	26.4956	2.346455	62.1709
0.399899	252.982	26.4956	2.753826	72.96446
0.42894	252.982	26.4956	3.193786	84.62151
0.45787	252.982	26.4956	3.666336	97.14204

Table -4: Pump power and flow rate with various pipe size and velocity.



Absolute roughness (mm)	Tank inlet pipe diameter	Relative Roughness	Friction factor	Velocity (m/s)	Flow rate (m^3/s)	Total pump head (m)	Pump Power (kW)
0.046	50	0.00092	0.019	14.8136	0.029	13	3.708
0.046	60	0.00077	0.0187	14.9399	0.042	13	5.384
0.046	70	0.00066	0.0184	15.0696	0.058	13	7.392
0.046	80	0.00058	0.0180	15.2026	0.076	13	9.741
0.046	90	0.00051	0.01772	15.3393	0.098	13	12.44
0.046	100	0.00046	0.0174	15.4797	0.122	13	15.50
0.046	110	0.00042	0.01708	15.6240	0.148	13	18.93
0.046	120	0.00038	0.01676	15.7725	0.178	13	22.74
0.046	130	0.00035	0.01644	15.9252	0.211	13	26.94
0.046	140	0.00033	0.01612	16.0825	0.248	13	31.56
0.046	150	0.00031	0.0158	16.2446	0.287	13	36.59
0.046	160	0.00029	0.01548	16.4116	0.330	13	42.06
0.046	170	0.00027	0.01516	16.5839	0.376	13	47.98
0.046	180	0.00026	0.01484	16.7618	0.426	13	54.37
0.046	190	0.00024	0.01452	16.9455	0.480	13	61.24
0.046	200	0.00023	0.0142	17.1353	0.538	13	68.62
0.046	210	0.00022	0.01388	17.3317	0.6	13	76.52
0.046	220	0.00021	0.01356	17.5351	0.666	13	84.96

3.1. Components Selection

3.1.1. Generator Selection

The success of any installation requires proper sizing of the generator. The power rating of the generator should be selected to have approximately 20% to 25% higher than the peak load. The peak load in this study is 25kW, therefore a 32kW (40KVA), 24 poles, 250 rpm and 50Hz generator is selected. This will allow the generator to operate comfortable at 80% of its full capacity and give room for future increase in load.

3.1.2. Turbine Selection

It is a good practice to select a turbine whose power is between 10% and 20% greater than that of the generator to compensate for the losses in the turbine and its accessories. Therefore, a 40kW Kaplan/propeller turbine with a synchronous speed of 253 rpm, angular velocity of 26.50rad/sec is selected for use.

3.1.3. Overhead Tank Selection

This should have the capacity to produce water power of 10% to 20% greater than the turbine power (i.e. 50kW) through the outlet pipe to the turbine. From table 1 and table 2, an overhead tank with a diameter of 1.45m, tank height of 3m, a head of 10m, a volume of 4954, 54 liters, a pipe diameter of 0.22m to the turbine and a flow rate of 0.533 m^3/s, has been selected.

3.1.4. Water Pump Selection

Pump are selected using the discharge (flow) rate and the pressure it will overcome while in operation as well as the voltage, power and frequency. The discharge rate should be sufficient to fill the overhead tank. The pressure depends on the vertical depth of the underground tank, the vertical elevation of the discharge pipe above the ground to the overhead tank and the pressure loss as results of the internal resistance of water flow in the internal surface of the pipe. Also, the pump power will have to be 10% to 20% higher than that of the turbine power to compensate for losses. The parameters selected for the pump to meet this requirements are steel commercial pipe of diameter of 0.19m, flow rate of pump pipe of 0.480m^3/s, pump power of 62kW, total head of 13m.

3.1.5. Inverter Selection

The pump power plays a very significant role in the selection of inverter. Inerter is selected with a higher power about 20% -30% higher than that of the pump power to compensate for losses and inefficiencies. Therefore, the total inverter power is 75kW.

3.1.6. Battery Selection

Battery bank is connected to solar PV to provide storage for energy for use when the sun is off. Although there are many types of batteries, the battery mostly used in renewable energy system to provide storage is the deep cycle battery. This type of battery can provide minimal current continuously for a long time and may be discharge to a depth of discharge DOD of 0.9. Batteries are rated for different amp-hours but the most common is the 150Ah battery. The time it takes to charge the connected battery determines the solar panel to be selected. The following expressions are used to calculate the power of solar PV;

$$P_{PV} = \frac{V_{batt} \times Ah_{batt}}{T_{pk}} \tag{23}$$

Where, P_{PV} is the PV panel power (W), V_{batt} is the battery voltage, Ah_{batt} is the capacity of the battery in amp-hour and T_{pk} is the period of peak sun a panel is required to charge the battery. For example there are 4-6 hours of sunshine hours/day and for a battery rated 12V, 150Ah, the power of the panel will be between 300W to 450W. This is the power required to charge a 12V, 150Ah battery for 6 and 4 hours respectively. To do this a panel with a higher power is most appropriate to select. For instance for a 300W battery power, a 350W panel is selected in order to accommodate the losses in the PV modules. Therefore the PV array will comprise of as many 350W as to provide the required water pump power.

A battery bank requires more than one 12V, 150Ah battery to supply the required power to the inverter. Therefore, the total power of the battery bank is given by the relationship;

$$P_{PV} = n \times \frac{V_{batt} \times Ah_{batt}}{\eta_b T_{pk}} \qquad 24$$

$$n = \frac{P_{PV} \times \eta_b T_{pk}}{V_{batt} \times Ah_{batt}} \qquad 25$$

Where, P_{PV} is the total power of the PV system, n is the number of batteries in the battery bank, η_b is the battery efficiency. This value of power should be 10% to 20% higher that of the inverter. That is, the total power of the PV system is 90kW and the number of 12V, 150Ah battery for the battery bank is 240.

3.1.7. Sizing of PV array

The PV array supplies power to the water pump. Therefore the power of the PV array is the power of the water pump plus 25% to compensate for the losses in the PV modules. The power for the system operating during sun periods of the PV array is calculated by;

$$PVarea = \frac{E_L}{H_{av} \times \eta_{pv} \times TCF} \qquad 26$$

Where, E_L is the daily energy required from the PV module (kWh/day), H_{av} is the average daily solar input (solar radiation) (kWh/m^2/day, η_{pv} is the PV conversion efficiency and TCF is the temperature correction factor. The theoretical maximium values of η_{pv} is 20% but can be less than this, between 6% and 15%. The solar PV is specified in wattage and voltage and its requirements cannot be changed. Battery bank is connected to solar PV to provide storage for energy for use when the sun is off.

The total power of the PV system is determined in section 3.1.6 to be 90kW and a panel with a power of 350W is selected. Therefore the PV array will comprise of as many 350W as to provide the required water pump power. The total number of solar PV in a PV array or system is given by;

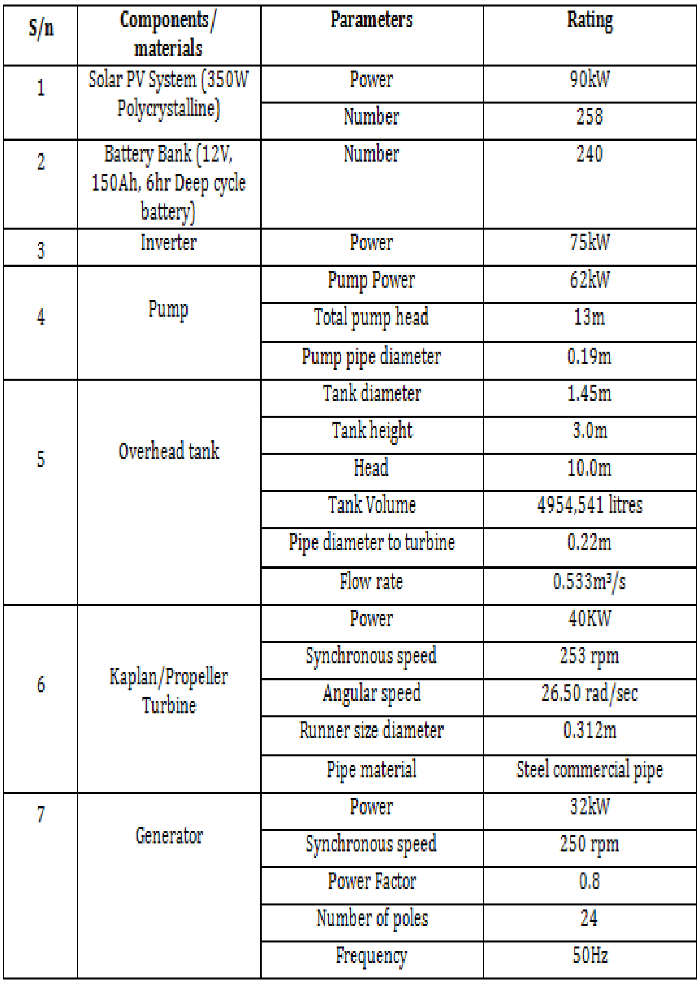
$$n_{pv} = \frac{P_{ArrayTotal}}{P_{panel}} \qquad 27$$

Where, $P_{ArrayTotal}$ is the total power of the PV array, P_{panel} is the power of one panel of the PV. Given the total power expected to be produce from solar PV system to be 90kW and the panel selected is of 350W, the total number of PV modules is 258.

3.1.8. Summary of components selection and sizing

Components rating and sizes selected to supply a 25kW load from a solar-pumped storage hybrid power system is shown in Table 5 below.

Table -5: Summary of components selection and sizing.



S/n	Components/ materials	Parameters	Rating
1	Solar PV System (350W Polycrystalline)	Power	90kW
		Number	258
2	Battery Bank (12V, 150Ah, 6hr Deep cycle battery)	Number	240
3	Inverter	Power	75kW
4	Pump	Pump Power	62kW
		Total pump head	13m
		Pump pipe diameter	0.19m
5	Overhead tank	Tank diameter	1.45m
		Tank height	3.0m
		Head	10.0m
		Tank Volume	4954,541 litres
		Pipe diameter to turbine	0.22m
		Flow rate	0.533m³/s
6	Kaplan/Propeller Turbine	Power	40KW
		Synchronous speed	253 rpm
		Angular speed	26.50 rad/sec
		Runner size diameter	0.312m
		Pipe material	Steel commercial pipe
7	Generator	Power	32kW
		Synchronous speed	250 rpm
		Power Factor	0.8
		Number of poles	24
		Frequency	50Hz

3.1.9. Known Parameters:

L1 = 4.5m, L2 = 7.5m, Z1 = 5m, Z2 = 12m, g = 9.81m/s

ρ = 1000Kg/m^3, Head (H) = 10m.

4. CONCLUSION

A solar-pumped storage hybrid power system required to supply 25kW of electric load has been successfully designed suitable for a rural communities that has adequate solar radiation. The proposed design can be used where there is solar energy resources but no hydro energy resources. The processes for the design have been discussed. All the components have been calculated and selected. These design is a good choice of implementation where there is no run off river or waterfalls and if implemented will provide a reliable and sustainable power supply to any rural communities with adequate solar radiation.

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