Solar-Powered Submersible Water Pump Selection and Sizing Calculations For Furrow Irrigation Application

Ikrang, Elijah George[1]
Department of Agricultural and Food Engineering,
University of Uyo, Akwa Ibom, Nigeria

Ezenwoko Jamike Iganatius[2]
Department of Space Applications and Research, Advanced Space Technology Applications Laboratory, Uyo, Akwa Ibom, Nigeria

Njoku Felix Anayo[3]
Department of Electrical/Electrc and Computer Engineering
University of Uyo, Akwa Ibon
Nigeria

***Abstract*— In this paper, solar-powered submersible solar water pump selection and sizing calculation for furrow irrigation application is presented. Specifically, the submersible solar water pump is applied in a 0.53 hectare case study carrot farm located in Gboko Benue State. First, the analytical expressions for the determination of the daily water demand for the case study carrot farm furrow irrigation system is presented. Also, the effective water flow rate and the water head for the solar pump that will supply the required water are also analytically determined. The case study farm location in Gboko Benue State has annual average peak sun hours of 5.27 hours per day. At 6 days irrigation cycle, the carrot farm required $10.29\ m^3$ of water per day at water discharge rate of 8.6 gallons per minute and water head of 49.2 m. The, requisite data from the power requirement charts of four different models of Sun Pumps submersible water pumps were used to select the pumps that will achieve the required flow rate and water head. The power requirement of each of the four selected pump models was compared. The SDS-Q-128 pump had the lowest power requirement of 518 watts with a total of 14 pumps. However, a signal SCS 7-210-60 water pump will require 774 watts to achieve the specified flow rate and water head. In all, this paper demonstrated that the selection of water pumps need to be carefully carried out so as to make selection that are optimal in terms of the power consumption of the water pumping system.**

***Keywords*— Furrow Irrigation, Water Pump, Submersible Pump, Peak Sun Hour, Total Dynamic Head, Submersible Pump, Solar Energy, Solar Water Pump.**

1. INTRODUCTION

Nowadays, the adoption of solar power system is on the increase [1,2,3,4,5]. This is due to the recurring drop in the cost of solar panels and also the need to adopt environmentally friendly energy systems [6,7,8,9,10,11,12,13,14,15]. Furthermore, solar power systems are mostly employed at remote locations that are far away from national electric grid. Particularly, in this paper, the use of solar powered water pump to supply the water required for irrigation of a carrot farm is presented. The carrot farm is irrigated using furrow irrigation method [16,17,18,19].

In order to select the appropriate water pump for the farm, the daily water demand, the water flow rate and the effective water head are needed. Generally, for any specified water head and water flow rate, there are several water pumps that can be selected to meet the specifications. However, different pumps selected with require different amount of power to deliver the same volume of water. As such, effort is made to select the water pumps that will require the minimal power for the given water demand.

In this paper, the analytical expressions and the procedure for selecting and evaluating the different pump models that can be used to deliver given water demand is provided. The analytical models and procedure are demonstrated using the water demand data to the carrot farm furrow irrigation system. The essence of the study is to provide researchers and practitioners with requisite tool that can enhance their ability to select water pumps with optimal power demand for their projects.

2 DETERMINATION OF WATER VOLUME REQUIRED FOR FURROW IRRIGATION PROCESS

The volume of water required per hectare for furrow irrigation of crops is given as [20];

$$n_{cn} = \left(\frac{10000-d_{bb}}{d_{wt}+d_{bb}}\right)+1 \qquad (1)$$

$$V_{fupha} = \left(\frac{h_w(d_{bb})(n_{cn})}{100}\right) \qquad (2)$$

Where V_{fupha} is the volume of water required per hectare, its unit is m^3/ha ; n_{cn} is the number of canals; h_w is the required crop's water height , its unit is cm; d_{bb} is the crop's bed to be distance , its unit is cm and d_{wt} is the width of , its unit is cm.

Let Q denote the water discharge rate in m^3/hr, n denote the number of days for one complete irrigation cycle, A_{fu} in m^2 denote the total hectares irrigated in one complete irrigation cycle, V_{pd} in m^2 denote the volume of water required for irrigation per day based on the irrigation cycle, A_{pd} in m^2 denote the area irrigated in one day, while T denote the number of hours irrigation is done per day, then;

$$V_{pd} = \left(\frac{A_{fu}}{n}\right)\left(\frac{h_w(d_{bb})(n_{cn})}{100}\right) \quad (4)$$

$$A_{pd} = \left(\frac{A_{fu}}{n}\right) \quad (5)$$

$$Q = \left(\frac{V_{pd}}{T}\right) \quad (6)$$

The case study farm is a 0.53 hectare carrot farm and according to available data in [20], it requires the following parameter; $d_{bb} = 100$ cm , $d_{wt} = 30$ cm , $h_w = 5$ cm . Since the farm is 0.53 hectares, then $A_{fu} = 0.53$ hectare. Also, a six (6) days irrigation cycle is adopted which means n = 6, then;

$$n_{cn} = \left(\frac{10000-d_{bb}}{d_{wt}+d_{bb}}\right)+1 = \left(\frac{10000-30}{100+30}\right)+1 = 77.69$$

$$V_{fupha} = \left(\frac{h_w(d_{bb})(n_{cn})}{100}\right) = \left(\frac{5(30)(77.69)}{100}\right) = 116.54\ m^3/ha$$

$$V_{pd} = \left(\frac{A_{fu}}{n}\right)\left(\frac{h_w(d_{bb})(n_{cn})}{100}\right) = \left(\frac{0.53}{6}\right)\left(\frac{5(30)(77.69)}{100}\right) = 10.29\ m^3/day$$

$$A_{pd} = \left(\frac{A_{fu}}{n}\right) = \left(\frac{0.53}{6}\right) = 0.08833\ ha/day = 883.3\ m^2/day$$

The farm is located in Gboko in Benue State with the annual average Peak Sun Hour solar of 5.27 hours/day which gives T = 5.27 . Hence, the water discharge rate , Q for the irrigation pump is given as;

$$Q = \left(\frac{V_{pd}}{T}\right) = \left(\frac{10.29}{5.27}\right) = 1.952 m^3/hr = 8.6$$

gallons/minute or 8.6gpm.

3 DETERMINATION OF THE PUMP TOTAL DYNAMIC HEAD

The Total Dynamic Head (TDH) is determined from the knowledge of the water pumping level (H_{PL}), lift from surface level (H_{LFSL}) and the pipe frictional loss (H_{PFL})as follows [21];

$$TDH = H_{PL} + H_{LFSL} + H_{PFL} \quad (7)$$

Let the total horizontal length of the pipe be denoted as L_h where L_h is determined from the horizontal distance from the water source to the water storage tank. Also, let the total length of the pipe be denoted as L_p, where L_p is the sum of the horizontal and vertical pipe lengths as follows;

$$L_p = H_{PL} + H_{LFSL} + L_h \quad (8)$$

Let h_{fp} denote the fittings equivalent of pipe length, n_f denote the number of fittings, and h_{pl} denote the pipe frictional loss per 100ft, then, the pipe frictional loss (H_{PFL}) is given as [22];

$$H_{PFL} = [L_p + n_f(h_{fp})]\left(\frac{1}{100}\right)(h_{pl}) \quad (6)$$

Hence,

$$TDH = H_{PL} + H_{LFSL} + [L_p + n_f(h_{fp})]\left(\frac{1}{100}\right)(h_{pl}) \quad (7)$$

Where TDH, H_{PL}, H_{LFSL}, L_p ,H_{PL} , H_{LFSL} and L_h are all in feet while h_{pl} and h_{fp} are in feet per 100 feet.

In this paper, the values of the water head parameters are as follows; $H_{PL} = 67$ ft; $H_{LFSL} = 60$ft; $L_h = 47$ ft and $n_f = 6$ standard 90º elbows. Furthermore, the fictional loss at the elbows in terms of equivalent pipe length and the pipe frictional loss in the ¾" plastic pipes are obtained using the Sta-Rite pipe friction loss charts [23] and their values are $h_{fp} = 5\ ft$ and $h_{pl} = 16.8$ ft $per\ 100\ ft$ of pipe length . Then,

$$L_p = H_{PL} + H_{LFSL} + L_h = 67 + 60 + 47 = 174 \text{ ft}$$

$$TDH = 67 + 60 + [174 + 6(5)]\left(\frac{1}{100}\right)(16.8) = 161.3 \text{ ft}$$

$$= 49.16424 \text{ m} \approx 49.2 \text{ m}$$

4 DETERMINATION OF THE HYDRAULIC POWER AND THE POWER REQUIRED FROM THE PV ARRAY

The hydraulic power of the pump for any given water flow rate and total dynamic head (TDH) can be determined analytically using available mathematical expressions and it can also be determined using available manufacturers power requirement charts and tables for their water pumps. In this paper, the manufacturer's datasheet and power requirement charts are used to determine the required pump hydraulic power based on flow rate (Q) and total water head (TDH) requirement specified from the analytical computations. Particularly, the hydraulic power of different pumps are considered for the same given Q and TDH. The results are compared and the best option is recommended for the given water pumping system.

A cut section of the power requirement table for Sun Pumps brushless DC submersible pump model SCS 7-210-60 BL is shown in Table 1 [24]. For the case study furrow irrigation water demand, the flow rate , Q is 8.6 gpm (gallons per minute) or 1.953272 m^3/hr and total water head (TDH) is 49.2 m or 161.3 ft. In Table 1, the data for the pump operating closest to the specified Q of 8.6 gpm and TDH of 49.2 m is highlighted in red color. Particularly, for the given pump dataset, at Q of 8.8 gpm and TDH of 49.3 m the required water electric power to drive the water pump is given by the column titled motor watts which after the 25% safety factor is included (by multiplying the motor watts by 1.25) gives the solar array watts. Also, the same row of the Table 1 shows that the pump operating efficiency at the given operating point of at Q of 8.8 gpm and TDH of 49.3 m is 35%.

Table 1 Power requirement table for Sun Pumps brushless DC submersible pump model SCS 7-210-60 BL (Source: [24])

PSI	TDH Feet	TDH Meters	Motor Voltage	Motor Amps	U.S. GPM	LPM	Motor Watts	Solar Array *Watts	Efficiency
45	104	31.7	60	12.8	10.8	41	768	960	27%
50	116	35.2	60	12.8	10.4	39	770	963	29%
55	127	38.7	60	12.9	10.0	38	773	967	31%
60	139	42.3	60	12.9	9.6	36	774	968	32%
65	150	45.8	60	12.9	9.2	35	775	968	34%
70	162	49.3	60	12.9	8.8	33	774	968	35%
75	173	52.8	60	12.8	8.3	32	769	961	35%
80	185	56.3	60	12.8	7.9	30	768	960	36%

The results of the selection in Table 1 shows that one Sun Pumps brushless DC submersible water pump model SCS 7-210-60 BL is needed to pump the water at the given flow rate and water head and the pump requires 774 watts of electrical power to do so. The same flow rate and water head can be achieved by other water pumps operating as single pump of operating as two or more pumps connected in series or in parallel or in a combination of series cum parallel connections. Also, each of the different pump connection configurations can result in a different power requirement. As such, in this paper, different pumps are considered at different connection configurations.

Importantly, when two or more pumps are connected in parallel, their water flow rates add up to give the effective water flow rate but the effective water head remains the same as the water head of the individual water pump. Conversely, when two or more pumps are connected in series, their water heads add up to give the effective water head but the effective water flow rate remains the same as the water flow rate of the individual water pump. In this study, four different Sun Pumps water pump models are considered, namely,

i. SunPumpsSDS Series Submersible PumpsModel SDS-Q-128 denoted as SDS-Q-128 (SDS-Q-128, 2018) [25].
ii. SunPumpsSDS Series Submersible PumpsModel SDS-Q-130 denoted as SDS-Q-130 (SDS-Q-130 , 2018) [26].
iii. SunPumpsSDS Series Submersible PumpsModel SDS-Q-135 denoted as SDS-Q-135 (SDS-Q-135 , 2018) [27].
iv. SunPumps Brushless DC Submersible Model SCS 7-210-60 BL denoted as SCS 7-210-60 (SCS 7-210-60 , 2018) [24].

For each of the pump models the required number of pumps in series and in parallel are determined along with the total number of pumps, the effective water flow rate, the effective water head, the effective required pump power and the normalized effective pump power at the specified water flow rate for the project. In Table 2 , the data obtained from the manufacturers datasheet for the pumps are stated as 'specified' whereas for the computed data items, the formula used is specified in the second row of the given column. Again, in Table 2, Q is the water flow rate given as 8.6 gpm and TDH is 49.2 m , as stated in row 1 column 1 of Table 2. The rest of the letters used in row 2 of Table 2 are the letters used to identify the specific column in Table 2. For instance, in column G, the formula is E*F which means that the values in column G are obtained by multiplying the content of column E by the content of column F.

For the given effective pump operating point defined by Q = 8.6 gpm and THD = 49.2 m and the individual pump operating point defined a discharge rate Q_i in gpm and water head H_i in meters , along with the pumps operating power , P_i in watts, then

The number of pumps in series, Ns where;

$$Ns = \left\lfloor \left(\frac{TDH}{H_i}\right) + 1 \right\rfloor \quad (8)$$

The number of pumps in parallel, Np where ;

$$Np = \left\lfloor \left(\frac{Q}{Q_i}\right) + 1 \right\rfloor \quad (9)$$

The required total number of pumps in the system, N where;

$$N = (Ns)Np \quad (10)$$

The effective total dynamic head of the system, TDH where ;

$$TDH = (H_i)Ns \quad (11)$$

The effective discharge rate of the system configuration x, Q(x) where ;

$$Q(x) = (Q_i)Np \quad (12)$$

The effective pump operating power of the system configuration x, P(x) where ;

$$P(x) = (P_i)N \quad (13)$$

The normalized pump operating power (Pn) at the specified Q flow rate;

$$Pn = \left(\frac{Q}{Q(x)}\right) P(x) \quad (14)$$

5 RESULTS AND DISCUSSION

The power requirement table for the four selected Sun Pumps solar pump model were used to obtain the the values of H_i, Q_i, P_i and the pump operating efficiency and these parameters were used in equation 8 to equation 14 to generate the results in Table 2.

Table 2 Power requirement table for Sun Pumps brushless DC submersible pump model SCS 7-210-60 BL

Q= 8.6 gpm THD = 49.2 m	A	B	C	D	E	F	G	H	J	K	L
	Specified	Specified	Specified	Specified	$\left\lfloor\left(\frac{TDH}{A}\right)+1\right\rfloor$	$\left\lfloor\left(\frac{Q}{B}\right)+1\right\rfloor$	E*F	A*E	B*F	C*G	$\left(\frac{Q}{J}\right)K$
Pump Model	TDH per pump (m)	Q per pump (gpm)	Pump Operating Power per pump at the operating point (watt)	Pump Operating Efficiency per pump	Ns (Number of pumps in series)	Np (Number of pumps in parallel)	N (Total number of pumps in the system)	Effective TDH (m)	Effective Q (gpm)	Effective Pump Operating Power (watt)	Normalized Power (watt) for Q flow rate
SDS-Q-128	24.6	1.23	37	0.51	2	7	14	49.2	8.61	518	517.4
SDS-Q-128	24.6	1.57	45	0.53	2	6	12	49.2	9.42	540	493.0
SDS-Q-128	24.6	2.6	81	0.49	2	4	8	49.2	10.4	648	535.8
SDS-Q-128	24.6	3.19	108	0.45	2	3	6	49.2	9.57	648	582.3
Sds-Q-130	24.6	1.27	45	0.43	2	7	14	49.2	8.89	630	609.4
Sds-Q-130	24.6	1.7	56	0.46	2	6	12	49.2	10.2	672	566.6
Sds-Q-130	24.6	2.9	100	0.44	2	3	6	49.2	8.7	600	593.1
Sds-Q-130	24.6	3.7	123	0.46	2	3	6	49.2	11.1	738	571.8
SDS-Q-135	24.6	1.56	46	0.51	2	6	12	49.2	9.36	552	507.2
SDS-Q-135	24.6	1.56	46	0.51	2	6	12	49.2	9.36	552	507.2
SDS-Q-135	24.6	1.9	58	0.51	2	5	10	49.2	9.5	580	525.1
SDS-Q-135	24.6	3.7	114	0.5	2	3	6	49.2	11.1	684	529.9
SDS-Q-135	24.6	4.3	145	0.45	2	3	6	49.2	12.9	870	580.0
SCS 7-210-60	24.6	1.5	130	0.17	2	6	12	49.2	9	1560	1490.7
SCS 7-210-60	49.3	3.3	341	0.3	1	3	3	49.3	9.9	1023	888.7
SCS 7-210-60	49.3	8.8	774	0.35	1	1	1	49.3	8.8	774	756.4

The results show that the combination with the lowest power requirement if the SDS-Q-128 pump in row 3 of Table 2; it has power requirement of 518 watts. However, a total of 14 pumps of model SDS-Q-128 are required to achieve the 518 watt pump system with two batches of 7 pumps connected in parallel and the two pump batches are connected in series. In any case, if economic analysis is conducted, the connection, installation and maintenance costs may discourage such choice.

If single pump is desired to meet the water pumping requirement, then, the SCS 7-210-60 with 774 watts will be recommended. Interestingly, the last column of Table 2 provided information that is used to effectively compare the different pump configuration on the basis of how much power that use to pump each unit of water flow rate. The smaller power required to pump a unit of water flow rate at the same water head gives better result. Again, the SDS-Q-128 pump in row 4 of Table 2 has the best results with 493.watts required to pump a unit of water flow rate. The irony is that the configuration with the lowest required effective electric power demand is not the one with the most efficient utilization of power to lift every gallon of water per minute through the specified water head. A closer look at the row 4 of Table 2 shows that the each of the SDS-Q-128 pump was operating at its highest efficiency of 53% whereas in the other rows of Table 2, the individual pumps in the system are operating at lower efficiency. The implication of the results in Table 2 is that, in selecting the water pump the operating efficiency of the individual pumps should also be considered .

6 CONCLUSION

The paper presented mathematical models and procedure for determination of the daily water demand for irrigating a carrot farm using the furrow irrigation method. The analytical models were also provided for the determination of the water flow rate and the total dynamic water head used in the selection of the solar water pump for the irrigation system.

Furthermore, analytical models and procedure were presented for the selection of different water pumps that can be used to realize the required water flow rate and water head. Particularly, in this paper, four different models of Sum Pumps submersible DC water pumps were considered and the number of pumps required for each pump model is determined along with the power requirement. The analytical expressions make it possible to determine the effective power required by the pumps selected. The selected pumps were also compared in terms of their required power. The results showed that the single pump configuration did not give the lowest power , rather a configuration that requires 14 water pumps gave the lowest power requirement. The ideas presented in this paper will provoke further studies on how to select solar water pumps to achieve optimal power requirement.

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