Numerical Analysis of PV Water Pumping System in Different Geographical Locations in Egypt

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Abstract*– The trending movement toward implementing renewable energy resources is still rising. Global warming and the many other hazardous effects made by fossil fuels motivated the whole world to transform to renewable energy resources. Water pumping is considered a primary load that consumes a high power conventionally supplied by diesel fuel. Therefore, Photovoltaic (PV) energy is increasingly employed in water pumping systems. This technology is based on using a PV array to convert solar energy into electrical energy to run a DC or AC motor-based water pump. To increase the employability of solar energy in water pumping systems, this paper presents a viable method of PV sizing to get the required PV modules to cover the load of water pumping. A presented method is a user-friendly tool based on economical values entered by a non-technician user. The main objective of the study is to cover the research gap found in the current PV sizing tools for water pumping systems by presenting a totally stand-alone PV system consisting of the solar array, inverter, solar charge controller, and circuit breaker, and a battery bank. Moreover, the total cost of the system installation and its payback period is calculated. The study has discussed the performance of the system in a different geographical location in Egypt. Finally, the carbon dioxide reduction saved by the system is measured. The results assure the effective utilization of solar energy as a driving energy source for the water pumping systems.

Keywords-- PV sizing, Solar pumping system, Standalone PV system, PV pumping cost, CO_2 reduction

I. Introduction

Due to the continuous improvements in the solar panels manufacturing and operation, there have been a tremendous reduction in the cost of PV modules. Therefore, the solar energy gained a great preferability as a renewable source of energy which motivates the integration of PV panels into buildings in what is called Building Integrated Photovoltaics BIPV. The research into integrating PVs and buildings has bloomed globally especially in those countries that have high solar radiation such as Egypt.

Water pumping is generally dependent on diesel fuel as a source of electricity. This system requires not only expensive fuel, but also creates a high noise and leads to the air pollution because of greenhouse gas emissions. Replacing the diesel fuel by PV array would create an environmentally friendly system with no emissions. The implementation of solar-powered water pumping systems has gained a wide acceptance in the recent years due to the increase in the diesel prices and the shortage of electricity. The overall capital cost along with the maintenance and operation cost of the diesel-based water pumping system is 2-4 times higher than solar-powered water pumping systems. Moreover, the unavailability of electricity in rural and remote areas made the solar-powered water pumping system a significant application in the irrigation applications in such areas.

Utilizing the solar energy in powering the pumping systems has under research for many years. Sharma [1] reported that installing solar powered water pumping systems is considered one of the best applications of BIPVs and has many advantages. It requires less maintenance than the conventional water pumping systems and can easily relate between the output power of the PV panels and the water demand. Ghonim [2] asserted that solar powered water pumping systems are expected to greatly decrease over the coming years. Hilarydoss [3] emphasized on cost reductions by concluding that water pumping by PV units cost about 0.055 USD/m^3 which is 300.0% lower than diesel-powered units. Moreover, Chandel [4] mentioned that the system consisting of water pumping and PV panels has a lifecycle of 20-25 years prevailingly exceeding the engine power pumping that has only 8 years age. Several authors [5-8] have conducted a TRNSYS (Transient System Simulation Tool) model to verify the performance of the water pumping system integrated with PVs equipped by a Maximum Power Point Tracker and the model confirmed its good performance when compared to the manufacturer's system. Raturi [9] used PVSYST to assess the performance of a solar-powered pump compared to a diesel-powered pump, and the study shows that solar energy meets the pump requirements and thus water demand for the case study, and power from the PV system can be used for other useful purposes like powering batteries for energy storage. Pardo [10] assured the importance of energy storage elements such as batteries to power electromechanical devices and how reliable they are. Adity et al. [11] claimed temperature variation affects the voltage of the batteries; however, this effect can be overcome by adding a pump controller which gives the pump the optimum voltage level it needs for operation. Jana et al. [12] Reported that water pumping applications require a high voltage to drive the load of the pump, so boost DC/DC converters are most suitable for pumping applications while buck and buck–boost converters are not.

Nomenclature

D The pipe diameter
R_e Reynold's number
K Surface roughness
ρ the density of water (1000 kg/m^3)
μ the dynamic viscosity of water (1.0016 mPa.sec at 20^{o}C)
hl The head losses
F The friction factor
Q The water flow rate (m^3/sec)
P_h Hydraulic power
H_t The total head
P_e The electric power supplied to the motor
η_t the total efficiency of the motor-pump system
P the total energy generation
Ppv the total hydraulic power required from the pump
AMIR the average incident radiation on the panels in (kWh/kWp)/(Month).
N_{pv} The number of PV panels required for installation
P1 the peak power generated by one panel
A_t The total installation area
Apv The area of one PV module
Pinv The inverter power rating
η_{inv} The inverter efficiency
CCR The solar charge controller rating (Amps)
I_{CB} The circuit breaker rating
V_{pu} The nominal pump voltage (380 V)
E_n Total energy required from the batteries (Wh/day)
P_T The total power produced by the PV system
B_{SS} The total battery system capacity (Ah)
Aut The number of days of autonomy
η_B The efficiency of the battery
DOD The duty cycle of the battery
V_B The nominal voltage of the battery
N_BB The number of batteries required
Cb The battery capacity (Ah)
E_{max} The maximum energy stored in the batteries (Wh)
A_{BT} The total battery system installation area
A_B The area of one battery

Rix [13] used PVsyst software tool to size the PV system required for water pumping application. It was observed that there are some faults in this method because it only allows for a sizing system accompanied by a storage tank to store the pumped water and no batteries can be utilized in this sizing method. Moreover, the system has limitations of the maximum height between the water level and the exit point that cannot exceed 5 meters which is unpractical for water reserved in underground wells with great depths. In addition, Ibrahim et al. [14] designed a tool for solar water pumping sizing in Egypt; their proposed system has a fault in the water demand calculation. The design is based on the total water demand instead of the average water demand which results excess energy requirements by the panel, so this increases the size of the system more than the application needs.

II. MATHEMATICAL MODEL

The objective of this model is to simulate and show results of an off-grid solar water pumping system; to show the system's function, the MATLAB code works on six steps:

- Determine the amount of incident solar radiation based on the user's location and PVs mounting type
- Calculate the average water demand based on the water bills for three different months.
- Calculate the hydraulic power needed from the pump based on the total dynamic head (TDH)
- Estimate the total power required from the PV system to cover the working of the pump
- Design a battery storage system to store excess energy
- Calculate the area required to install the system

Fig. 1 shows the flow chart that briefly describes the work of the MATLAB code.

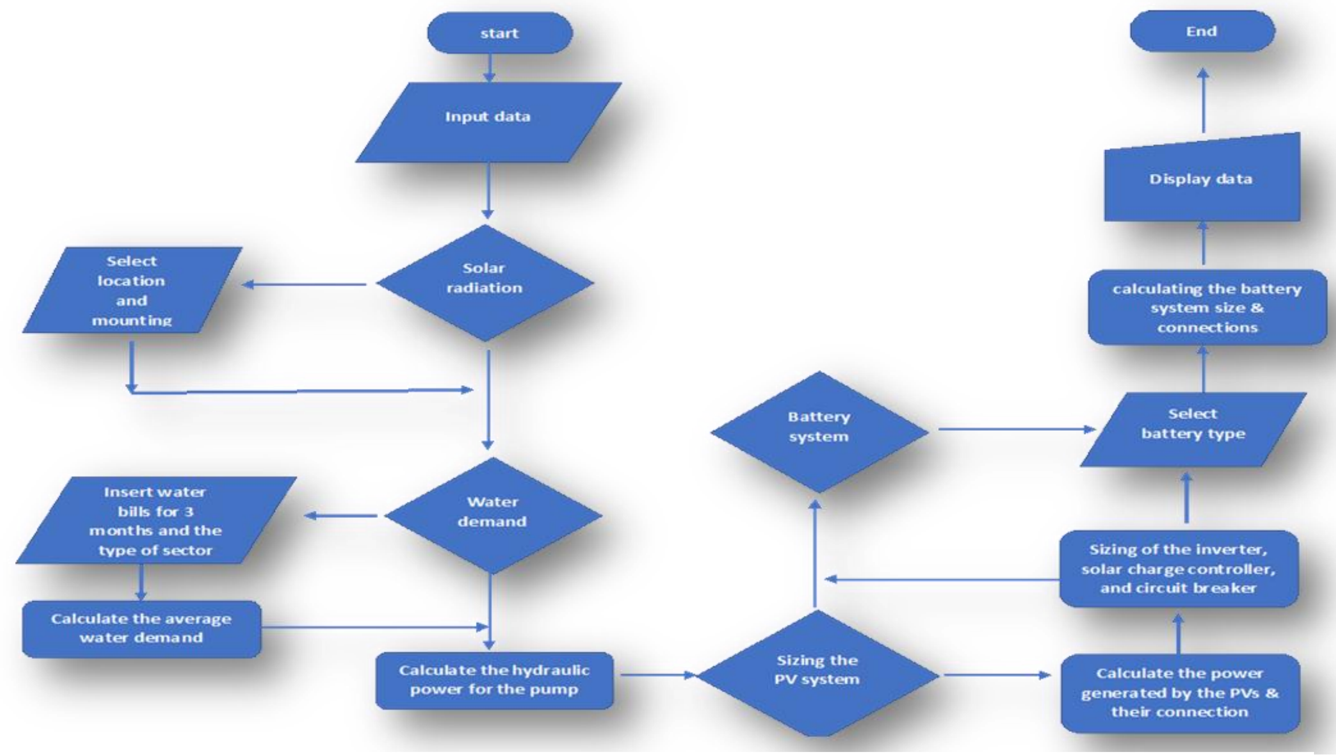

Fig. 1: The flow chart showing the successive processes used in the code

The successive steps used in this model aim to finally find the number of PV modules that are needed to satisfy the pumping system need. The processes are described in detail as follows:

Estimation of the incident solar radiation amount:

Initially, users are requested to insert the data necessary for irradiation estimation, namely the location, mounting system type, sector type, and the battery type. Next, it will be required to insert the monthly water bills for different months throughout the year to calculate the average monthly water bill. Finally, the average water bill, together with the irradiation data, will be used as input to evaluate the size of the pump needed followed by the PV and battery systems.

The water demand evaluation:

As an unprecedented method to evaluate the water demand that needs to be pumped, the proposed method depends on actual monetary values entered by the user. The user is asked to input three different inputs for three different months. The average value of the three bills is the value upon which the sizing depends. This value has a measuring unit of EGP/Month. Dividing this value by the Egyptian tariff (EGP/m^3) which is already defined by the Egyptian government would get a clue the water volume demanded every month (m3/Month) by the user. By this, an accurate value of the water volume demanded by the user is determined.

The total head measurement:

The total head is the summation of both the heights to which the water is pumped, and the head losses resulted from the water flow inside the pipe. The height needed for the water to be pumped is assumed to be 10 meters while the head loss is a function of the friction factor of the water inside the pipe. The friction factor can be estimated for a pipe according to Moody equation:

$$\frac{1}{(F)^{0.5}} = -2\,log\left(\frac{K}{3.7D} + \frac{2.51}{R_e * (F)^{0.5}}\right) \qquad (1)$$

Reynold's number also depends on the flow speed as follows:

$$R_e = \frac{\rho V D}{\mu} \qquad (2)$$

Then, the head loss value is given by the Darcy-Weisbach equation as follows:

$$hl = F\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right) \qquad (3)$$

By summing the head loss and the pumping height, the hydraulic power needed for the water is determined.

The hydraulic power needed:

The hydraulic power needed by the pump is given by the following formula:

$$P_h = PQ = \rho g Q H_t \qquad (4)$$

Then, the hydraulic power needed for the water by the pump is supplied by the motor as electric power given by the formula:

$$P_e = \frac{P_h}{\eta_t} \qquad (5)$$

Where the sizing of the amount of PV panels needed to supply the water pumping system depends on this electric power needed by the motor.

Estimating the PV system power based on the irradiation data:

The type of solar module used is Jinko solar (335 W, poly). Based on the irradiation data and the pump total hydraulic power needed for the water flow, the total power required by the pump to operate during the day is used to size the appropriate PV system for the pumpp. The pump works 10 hours per day divided between both the PV and battery systems each working 6 hours and 4 hours respectively.

The following equation is used to determine the energy generated by the PV system:

$$P = \frac{Ppv \times 6}{AMIR \times 0.78 \times 30} \qquad (6)$$

Where the operating factor is assumed to be 0.78. The number of PV panels is determined as follows:

$$N_{pv} = \frac{P}{P_1} \qquad (7)$$

Panels installation area:

The installation area of the PV system is simply the product of the number of panels and the area of one module. Furthermore, the mounting area of the system must account for spacing between each array to prevent shadowing effect which is 170 cm according to dimensions of one module.

$$A_t = N_{pv} * \left(A_{pv} + 1.7\right) \qquad (8)$$

The inverter rating:

Subsequently, it is necessary to determine the inverter power which is a key component in the total installation. Based on the power generated by the PV system, the inverter power is calculated using the equation:

$$P_{inv} = \frac{(P/0.8)}{\eta_{inv} * 1.2} \qquad (9)$$

assuming DC/AC Ratio to be 1.2 and 0.8 lagging power factor.

Solar charge controller rating:

Next, the solar charge controller rating must be determined; its function is to modify the variable DC output coming out of the panels into a constant DC output by eliminating electricity fluctuations to maintain a steady power supply to the pump and to charge the batteries as well. The rating is calculated using the short-circuit current of one panel using the equation:

$$CCR = \frac{N_{pv} \times I_{sc}}{1.3} \qquad (10)$$

Where the losses are assumed to be 0.3 due to wiring and conversion efficiency.

Circuit breaker rating:

Next, it is required to determine the circuit breaker rating which is a function of the inverter rating and the pump voltage, and it is calculated using the equation:

$$I_{CB} = \frac{P_{inv}}{\sqrt{3} \times V_{pu}} * 1.25 \qquad (11)$$

Where it is assumed that wiring and resistive losses account for 25%.

The battery system:

The battery storage system is essential for storing energy for later use either at night or at days of autonomy; days of autonomy are the days in which there is no sun. The design includes two types of batteries to choose from which are Lead-acid and Lithium-ion batteries.

- *Battery system size*

  First, the energy required from the batteries is determined from the following equation:

$$E_n = P_T * 4 \qquad (12)$$

  Where the number of working hours of the batteries is 4 hours/day.

  The equation used for calculating the system size:

$$B_{SS} = \frac{E_n \times Aut}{\eta_B \times DOD \times V_B} \qquad (13)$$

- *The number of batteries used for the system*

$$N_{BB} = \frac{B_{SS}}{Cb} \qquad (14)$$

- *The maximum energy stored in the batteries*

$$E_{max} = N_B \times Cb \times V_B \qquad (15)$$

- *Installation area of the batteries:*

  It is advisable to have spacing between batteries in their installation to avoid thermal effect of one battery on the other which, if not avoided, decreases the overall efficiency of the battery, and in the design the spacing accounts for 1.3 cm^2. The installation area equation of the battery system is:

$$A_{BT} = N_{BB} * (A_B + 0.013) \qquad (16)$$

III. Results

The model can size the PV standalone system that is required for the water pumping system in four different locations in Egypt. The four locations include Cairo, Alexandria, Aswan and Hurghada that show various monthly radiation data as shown in TABLE1:

TABLE1: THE MONTHLY AVERAGE RADIATION DATA IN THE FOUR LOCATIONS

Location	Irradiation (kWh/kWp)/(Month)
Cairo	192.2
Alexandria	189.8
Aswan	220.3
Hurghada	219.1

The model was tested in the four locations for the three different sectors including the residential, commercial, and agricultural sectors. The three water bills entered to the model are in direct relation with the sector applied. The residential sector has the least amount of bills while the agricultural sector pays the most and the commercial sectors falls in between. Moreover, the mounting system for the residential system is of rooftop mount while both the commercial and agricultural sectors are of ground mounted type. The same battery type of lead acid battery is utilized in all cases.

Cairo:

TABLE2: THE SIZING DATA FOR THE FOUR SECTORS IN CAIRO

Result	Residential	Commercial	Agricultural
Number of PV modules	5	13	31
Generated power (KW)	1.54	4.23	10.2
Area of the system (m^2)	18.2	47.32	112.84
Inverter size (KW)	1.694	4.639	11.2
Solar CC size (A)	39.84	103.6	247
CB size (mA)	3.2	8.8	21.3
Number of batteries	16	18	102
Annual CO_2 savings (Kg)	1192.95	3265.45	7903.44
Total cost of the system	98384.7	117463.28	622761.16

Alexandria:

TABLE3: THE SIZING DATA FOR THE FOUR SECTORS IN ALEXANDRIA

Result	Residential	Commercial	Agricultural
Number of PV modules	5	13	31
Generated power (KW)	1.56	4.28	10.3
Area of the system (m^2)	18.2	47.32	112.84
Inverter size (KW)	1.716	4.697	11.2
Solar CC size (A)	39.84	103.6	247
CB size (mA)	3.2	8.8	21.3
Number of batteries	16	18	102
Annual CO_2 savings (Kg)	1192.87	3265.94	7902.2
Total cost of the system	98679.95	117500.2	624573.94

Aswan:

TABLE4: THE SIZING DATA FOR THE FOUR SECTORS IN ASWAN

Result	Residential	Commercial	Agricultural
Number of PV modules	4	12	27
Generated power (KW)	1.34	3.69	8.93
Area of the system (m^2)	15.2	43.68	98.28
Inverter size (KW)	1.47	4.04	9.795
Solar CC size (A)	38.1	103.6	215.169
CB size (mA)	2.8	7.68	18.3
Number of batteries	14	16	42
Annual CO_2 savings (Kg)	1020.8	3265.24	7902.93
Total cost of the system	90158.2	110946.2	251074.96

Hurghada:

TABLE5: THE SIZING DATA FOR THE FOUR SECTORS IN HURGADA

Result	Residential	Commercial	Agricultural

Number of PV modules	5	12	27
Generated power (KW)	1.35	3.71	8.98
Area of the system (m^2)	18.2	47.32	98.28
Inverter size (KW)	1.486	4.069	9.849
Solar CC size (A)	39.84	103.6	215.169
CB size (mA)	2.8	7.7	18.7
Number of batteries	16	18	42
Annual CO_2 savings (Kg)	1192.78	3264.99	7902.33
Total cost of the system	95538.19	109671.58	251759.99

The results show the system effectiveness in generating sensible data of sizing that are related to the system water needs. The data generated for the agricultural sector are the highest since it is the largest water-consuming system. On the other hand, the data produced for the residential sector in the four locations are the lowest since it is the smallest water-consuming sector. The commercial sector falls in between the above-mentioned sectors. Furthermore, it is sensible when it is compared to the location and the radiation data given in TABLE1. The results show that the PV modules required in Aswan and Hurghada are lower than that needed in both Cairo and Alexandria. It was expected since the radiation in Aswan and Hurghada is higher than that in both Cairo and Alexandria.

IV. CONCLUSION

In conclusion, this work presents a sizing tool for calculating the required PV modules and battery system size for off-grid water pumping systems. The design focuses on the low-voltage sector being either residential, commercial, or agricultural with each sector having an assigned water tariff which is used along with the average water bills throughout the year to calculate the hydraulic load needed from the pump; this hydraulic power in turn depends on the total head, and the flow rate. Furthermore, the pump power demand is used to evaluate number of PV panels required for installation along with the power produced from the panels. Afterwards, the ratings of the necessary equipment including the inverter, solar charge controller, and the circuit breaker are determined based on the panels' data. Additionally, the battery system size and number of batteries are calculated to account for the pump working at night or at days of autonomy. This sizing model was effective in generating accurate sizing data for the different sectors in the various locations.

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