# PERFORMANCE PREDICTION OF A PROPOSED PHOTOVOLTAIC WATER PUMPING SYSTEM AT SOUTH SINAI, EGYPT CLIMATE CONDITIONS

**Helmy E. Gad**

Mechanical Power Engineering Department, Faculty of Engineering,
Mansoura University, El-Mansoura 35516, Egypt
E-mail: he_gad@yahoo.com

## ABSTRACT

The use of photovoltaic (PV) array for pumping water is one of the most promising techniques in solar energy applications. Due to the increased use of water pumping systems in urban areas, more attention has been paid to their design and performance prediction under different operating conditions. In this paper, a methodology is developed for performance perdition of a proposed direct coupled PV water pumping system in St. Catherine area, South Sinai, Egypt. The system consists of a four modules PV array (with 72 PV cells in each module), pump controller and a 12 VDC submerged pump. The target of the system is to supply at least 8 m$^3$ from the well at a total head of 30-40 m. A computer simulation program is developed to predict the performance of the proposed system. This program uses models for solar radiation data, the PV array with intermittent tracking and the pump. The model is adapted to simulate the hourly performance of the system at any day of the year, under different PV array orientation. The pump controller characteristics are also varied to achieve the best performance for the proposed system. Results are shown in graphical form.

**Keywords:** Photovoltaic, solar water pumping, performance, South Sinai.

## NOMENCLATURE

| | |
|---|---|
| A | Array area (m$^2$) |
| B | Beam solar radiation intensity (W/m$^2$) |
| D | Diffuse solar radiation intensity (W/m$^2$) |
| F | Photovoltaic cell fill factor |
| G | Global solar radiation intensity (W/m$^2$) |
| H | Total head of the pump (m) |
| h | Solar hour angle |
| I | Current (A) |
| $K_{td}$ | Daily average clearness index |
| L | Latitude angle of the place |
| m | Air mass ratio |
| N | The day number starting from January first |
| n | Number of cells in the PV array |
| P | Pump power (W) |

| | |
|---|---|
| $R_b$ , $R_d$ | Tilt factor for beam and diffuse solar radiation intensity respectively |
| T | Temperature (°C) |
| t | Local time |
| Q | Pump flow rate (m$^3$/hr) |
| V | Voltage (V) |

**Subscripts**

| | |
|---|---|
| c | Tilted surface of the PV array |
| d | Daily |
| h | Horizontal |
| o | Outside the atmosphere |

**Greek symbols**

| | |
|---|---|
| $\alpha$ | Sun altitude angle |
| $\beta$ | PV array tilt angle |
| $\delta$ | Solar declination angle |
| $\eta_p$ | Pump efficiency |
| $\eta$ | The PV array efficiency |

## INTRODUCTION

Many small communities all over the world depend on the ground water for their domestic use and agriculture activities. Sinai, Egypt is one of these places that have abundant ground water. Local people use small diesel generators to supply the necessary electric power for pumping water from the wells. Many of these people are living far away inside mountains where the approach roads for them to get the diesel fuel and spare parts are difficult. The problem is getting more worth with the latest increase in the fuel cost. Besides, the need for decreasing the air pollution and green house gases in the Earth’s atmosphere makes more restrictions on the use fossil fuel. The best choice to face this situation is to facilitate the wells with suitable solar water pumping systems. Such systems usually use PV array to convert the solar radiation into electric direct current.

Today, there are many solar pumping systems in the world powered by PV arrays. Solar pumps are particularity useful for intermediate applications like small villages and moderate agricultural needs (100-1000 inhabitants). The use of PV power is the preferred choice, especially where there is an adequate solar resource and small water demand. Many researchers have studied the performance of photovoltaic powered water pumping systems. Several experimental studies and theoretical analyses of PV pumping system have been published. The direct coupled PV pumping system is seen to be more suitable for use in these situations, since it is simple and lower cost. Other systems use DC/AC inverters and AC pumps. The direct coupled PV pumping system under steady state conditions has been studied and analyzed [1-5]. The performance of a PV pumping system has been studied with different modeling techniques, and the optimal solar array configurations are tested.

As a first step, the Egyptian government has decided to supply about 50 wells in St. Catherine area, South Sinai, Egypt with direct coupled PV water pumping systems.

The European Union will cover the project cost. The proposed system must supply, at least, 8 $m^3$/day from the well at total head 30-40 m. In the present work, a modeling of the system on the basis of clear sky conditions has been carried out. The system performance under different tilt array angles and solar radiation data is obtained. The tender conditions and specifications of the system components are used as input data to the computer program to predict the daily pumped water all over the year.

## Description of the System

The proposed system consists mainly of a PV array (1), pump controller (2) and a submerged pump (3) as shown in Fig. 1. The pump controller switches on the pump when the PV array output current reaches a suitable operation level and switches it off when the current is lower than that. The pump controller has also a facility to switch off the pump when the water level in the well is lowered to a certain predetermined value in order to avoid the pump dry operation condition. The pump should not be kept in dry running for more than 2-3 minutes. The pump is also switched off when the water in the storage tank reaches a maximum level and the tank is full. The solar pumping system may also contains a small battery bank and a solar charge controller to regulate and insure power supply to the pump in cloud sky condition and provide light at dark nights.

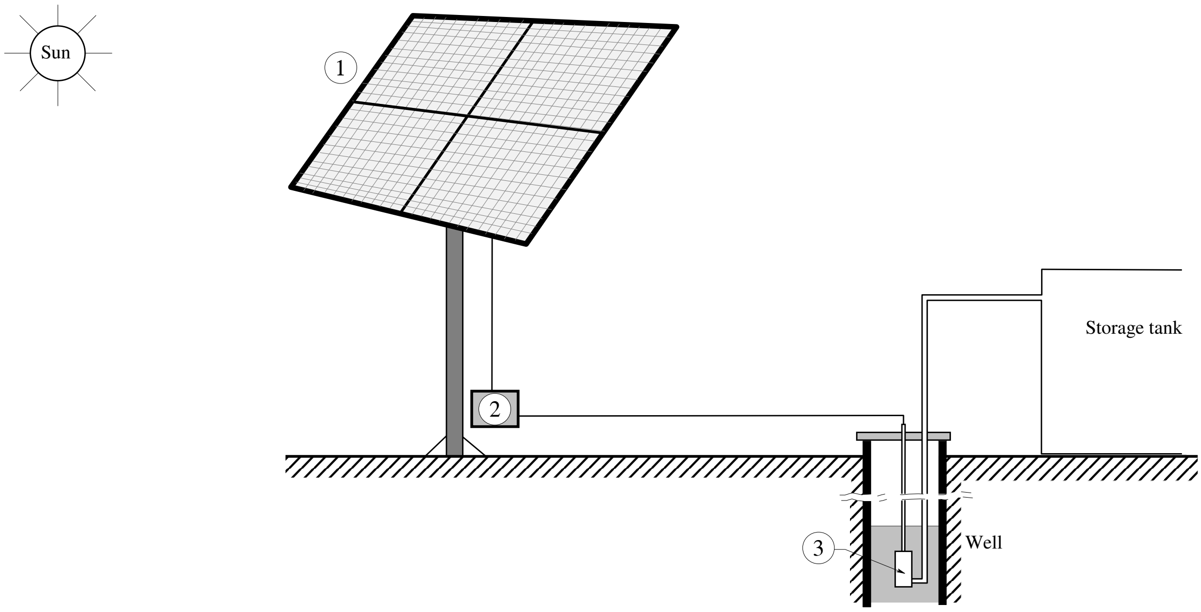

**Fig. 1. A schematic diagram of the proposed PV water pumping system.**

The PV array consists of 4 modules connected in series and in parallel to produce the necessary 12 VDC. Each module contains 72 photovoltaic cells. The pumping daily flow rate is 8 $m^3$/day (at least) all over the year to a storage tank (4-6 $m^3$) just over the ground level near the well.

The most important problem in solar energy applications such as the pumping system is the periodic nature of the solar radiation. Early morning and late afternoon, the solar radiation intensity reduces dramatically and so the DC current produced from the PV array. This problem can be successfully solved by using the pump controller which is a microprocessor used to monitor power between the PV array and pump.

## THE SYSTEM MODELING

The mathematical modeling of the PV pumping system includes the solar radiation data, PV array and the pump. The pump controller function is also considered.

### Modeling of solar radiation data

Solar radiation data is essential for design and sizing the PV pumping system since power output from the PV array depends on its value. Neglecting the reflection component, the hourly value of total solar radiation intensity on the array tilted surface, $G_c$ can be calculated from Duffie and Beckman [6] as,

$$G_c = R_b B_h + R_d D_h \tag{1}$$

Where, $B_h$ and $D_h$ are the beam and diffuse solar radiation component intensities respectively on a horizontal surface,

and $R_b$ and $R_d$ are the beam and diffuse tilt factors respectively given by,

$$R_b = \frac{\cos(L-\beta)\cos\delta\cos h + \sin(L-\beta)\sin\delta}{\cos L\cos\delta\sin h + \sin L\sin\delta} \quad \text{and} \quad R_d = \cos^2\left(\frac{\beta}{2}\right) \tag{2}$$

Where, L is the latitude angle of the place and β is the array tilt angle,

h solar hour angle defined by $h = (12 - t)\times 15^o$ (t is the local time, hr),

and δ is the solar declination angle defined by,

$$\delta = 23.5 \sin\left[\frac{360}{365}(N + 284)\right] \tag{3}$$

Where, N is the day number starting from January first.

The hourly global solar radiation intensity on a horizontal surface, $G_h = B_h + D_h$ in clear sky model is given by Meinel and Mainel [7] as,

$$G_h = G_{oh}\,(0.7)^{m^{0.678}} \tag{4}$$

Where, $G_{oh}$ is the extraterrestrial irradiance on horizontal surface given by Markvart [8] as,

$$G_{oh} = G_{sc}\left[1 + 0.033\cos\left(\frac{2\pi N}{365}\right)\right](\cos L\cos\delta\cos h + \sin L\sin\delta) \tag{5}$$

$G_{sc}$ is the solar constant = 1367 W/m$^2$

and, m is the air mass ratio calculated for clear sky condition by Kreith and Kreider [9] as,

$$m = \left[1229 + (614\sin\alpha)^2\right]^{0.5} - 614\sin\alpha \tag{6}$$

where, $\alpha$ is the sun altitude angle obtained from,

$$\sin\alpha = \cos L \cos\delta \cos h + \sin L \sin\delta \tag{7}$$

The data collected from several stations by Collares-Pereira and Rabl [10], has shown that, the measured ratio, $r_d$ of diffuse irradiance on a horizontal surface, $D_h$ to the diffuse daily irradiation, $\overline{D}_h$ can be estimated by,

$$r_d = \frac{D_h}{\overline{D}_h} = \frac{G_{oh}}{\overline{G}_{oh}} \tag{8}$$

Where, $\overline{G}_{oh}$ is the daily extraterrestrial solar radiation on a horizontal surface that can be obtained from Iqbal [11] as,

$$\overline{G}_{oh} = \frac{24}{\pi} G_{sc}\left[1 + 0.033\cos\left(\frac{2\pi N}{365}\right)\right](h_s \sin L \sin\delta + \cos\delta \cos L \sin h_s) \tag{9}$$

Where $h_s$ is the sunset hour angle obtained from Duffie and Beckman [6] as,

$$h_s = \cos^{-1}(-\tan L \tan\delta) \tag{10}$$

The daily diffuse solar radiation on a horizontal surface, $\overline{D}_h$ can be estimated in terms of the daily average clearness index, $k_{td}$ from Collares-Pereira and Rabl [10] as,

$$\overline{D}_h = F_d\, \overline{G}_h \tag{11}$$

$$\text{Where, } F_d = 1.88 - 2.272\,k_{td} + 9.473\,k_{td}^2 + 21.856\,k_{td}^3 + 14.648\,k_{td}^4$$
$$= 0.99 \quad \text{if} \quad k_{td} \le 0.17$$

The hourly beam solar irradiance, $B_h$ can be obtained from,

$$B_h = G_h - D_h \tag{12}$$

Finally, the hourly average total solar radiation intensity on the array tilted surface, $G_c$ at any day of the year can be obtained from equation (1).

## Optimal PV array tilt angle

For maximum utilization of solar radiation, an array full-tracking unit should be used. But the addition of such unit results in a significantly higher cost. The fixed tilt angle array (south facing) yields maximum output allover the year if its tilt angle is adjusted equivalent to the latitude angle of the place, L. This system is expected to have a maximum yield in spring and autumn seasons, but the maximum water demand is expected in the summer season. The slope of the array can be adjusted manually once each month. This approach has been considered in some previous studies, but the frequency of readjusting is seen to be much for those simple people. Therefore, it is intended to use a simple-low cost manual tracking mechanism in which the PV array is facing south with a tilt angle that can be adjusted once each season. In this case, the system has only three position points; the first is suitable for winter, the second in summer and the third is suitable for equinoxes (spring and autumn).

## Modeling of the photovoltaic array

According to the the tender conditions and specifications, the PV array consists of 4 modules with the following characteristics:

- Approximate dimensions of each module 0.8 x 1.6 m with 72 cells.
- Type of cells: Silicon mono crystalline, $I_{sc} = 5.65$ A and $V_o = 0.617$ V.
- Power of each module: about 180 W (power tolerance ± 5%).
- Module efficiency: not less than 13%.

The modules will be connected in series and parallel to provide the necessary voltage to operate the DC submersible pump.

The I-V characteristic equation of the photovoltaic cell is given by Roger and Jerry [12] as,

$$I = I_L - I_o \left[ \exp\left(\frac{q\,V}{k\,T}\right) - 1 \right] \tag{13}$$

Where, $I_L$ is the cell (light) current which is equal to the short circuit current (at V=0)
$I_o$ is the reverse saturation (dark) current, A
$q = 1.6\mathrm{x}10^{-19}$ Coul
$k = 1.38\times 10^{-23}$ J/K
and T is the cell temperature, K

To determine $I_o$ , the current I, in equation (13) is set to zero. In this case, V is equal to the open circuit voltage, $V_o$, yielding the result:

$$V_o = \left(\frac{kT}{q}\right) \mathrm{Ln}\,\frac{I_L + I_o}{I_o} \cong \left(\frac{k\,T}{q}\right) \mathrm{Ln}\,\frac{I_L}{I_o} \qquad \text{since } I_L >> I_o \tag{14}$$

$$I_o = I_L \exp\left(-\frac{q\,V_o}{k\,T}\right) \tag{15}$$

To a very good approximation, the cell light current, $I_L$ is directly proportional to the cell irradiance. Therefore, if the cell current, $I_L(G_o)$ is known under standard test conditions, $G_o = 1000$ W/m$^2$ at 1.5 air mass ratio and 25 °C. Then the cell light current $I_L(G)$ at any other irradiance, G is given by,

$$I_L(G) = \left(\frac{G}{G_o}\right) I_L(G_o) \tag{16}$$

From the manufactures catalogues of a typical Silicon mono crystalline photovoltaic cell, the value of $I_L(G_o)$ is 5.65 A and $V_o = 0.617$ V.

The above equations can be used to obtain the current, I and voltage, V produced by the photovoltaic cell at different operating conditions. The power output of the PV array, P is given by,

$$P = F\,I\,V \tag{17}$$

Where, F is the cell fill factor which is a measure of the cell quality. The typical fill factor for PV cells, depending on the technology, may vary from 0.5 to 0.82. An empirical expression for the fill factor is given by Green [13] as,

$$F = \frac{V_o - (k\,T/q)\ \mathrm{Ln}\left(q\,V_o / k\,T + 0.72\right)}{V_o + k\,T/q} \tag{18}$$

The PV array efficiency can be estimated from,

$$\eta = \frac{n\,P}{A\,G_c} = \frac{n\,F\ I\,V}{A\,G_c} \tag{19}$$

If the cell is operating at the maximum point power, the maximum power $P_m$ will be,

$$P_m = F\,I_m\,V_m \tag{20}$$

The cell I-V performance is also sensitive to its operating temperature. The open circuit voltage of a silicon cell decreases by 2.3 mV corresponding to 1 °C, which amounts to approximately 0.5% / °C as reported by Eikelboom and Jansen [14]. On the other hand, $I_{sc}$ remains nearly constant with temperature change. As a result, the cell power also decreases by the same percentage. The cell temperature, $T_c$ can be estimated quite accurately according to Markvart and Castañer [15] as,

$$T_c = T_a + \frac{T_N - 20}{800} G_c \tag{21}$$

Where, $T_a$ is the ambient air temperature, °C
and $T_N$ is the nominal operating cell temperature, °C.
$T_N$ is the temperature the cells that will reach when operated at open circuit in an ambient temperature of 20 °C at m = 1.5, irradiance conditions G = 800 W/m$^2$ and a wind speed less than 1 m/s. In St. Catherine area, Sinai (1670 m above sea level), the monthly average ambient temperature is given in Table 1 as obtained from the NASA website.

**Table 1. Ambient temperature in St. Catherine area, Sinai, Egypt.**

| Month | Max. temp, °C | Min. temp., °C |
|---|---|---|
| March and September | 20 | 8 |
| June | 26 | 12 |
| December | 12 | 1 |

Solving equations from (13) to (21) simultaneously, the output current and voltage from the PV array can be obtained.

## Modeling of the pump

The pump must be a heavy duty type to withstand operation under severe conditions with a nominal voltage 12 VDC.

The electrical power consumption by the pump, P (W) is given by,

$$P = \frac{\rho g H Q}{\eta_p} \qquad (22)$$

Where, H is the total head (m), Q is the water flow rate ($m^3/s$) and $\eta_p$ is the overall pump efficiency.

## RESULTS AND DISCUSSION

A computer program using Matlab (version 7.0) is developed and employed to solve the above equations. The intensity of global solar radiation on a horizontal surface, $G_h$ for St. Catherine area, Sinai is obtained as function of time (with 0.01 hr step) using equations from (1) to (12).

Results for the summer solstice day (21 June), equinoxes (21 March and September) and winter solstice day (21 December) are shown in Fig. 2. The maximum values of solar radiation intensity (at 12 noon) are 920, 810 and 510 $W/m^2$ respectively. The same results obtained for a south facing PV array with tilt angles 15, 30 and 45° are shown in Figs. 3, 4 and 5 respectively. These tilt angles (L-15, L and L+15) are the optimum tilt angles for summer solstice, equinoxes and winter solstice as reported in Duffie and Beckman [6].

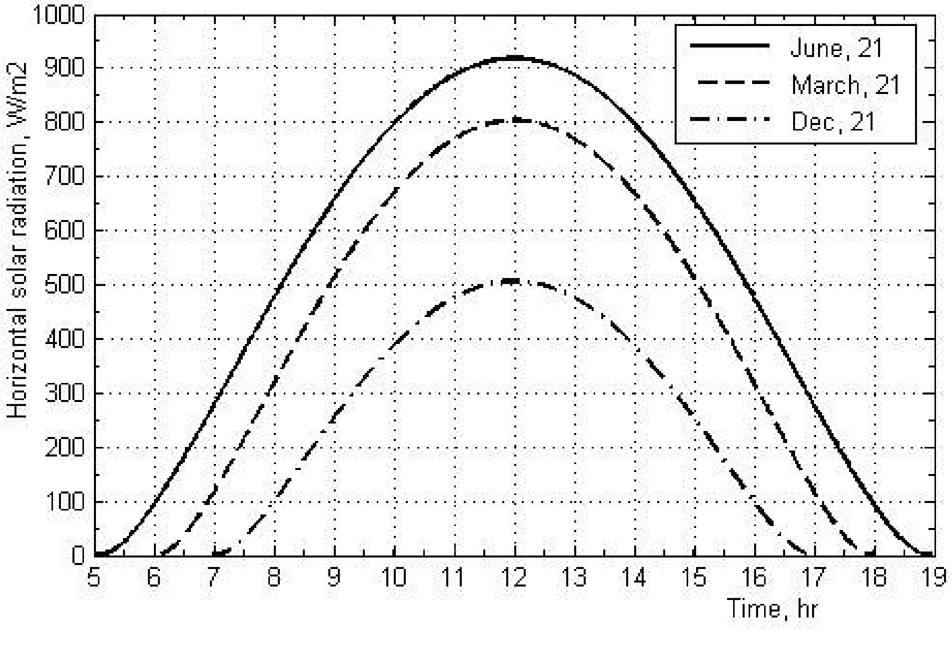

**Fig. 2. Global solar radiation intensity on a horizontal surface (Latitude=30° N).**

Figures 3, 4 and 5 show that, in summer solstice and equinoxes, the solar radiation intensity on the array surface is slightly reduced by increasing the tilt angle, while it is considerably increased in the winter. Therefore, some designers prefer to fix the array at a tilt angle L+15° (= 45° in this case), since the results for all seasons are close as shown in Fig. 5. However, it is decided to change the tilt angle seasonally to be 45° during winter, 30° in equinoxes and 15° in summer. In this case, results will be higher and closer. The above data are used as input data to solve the modeling equations for the PV array.

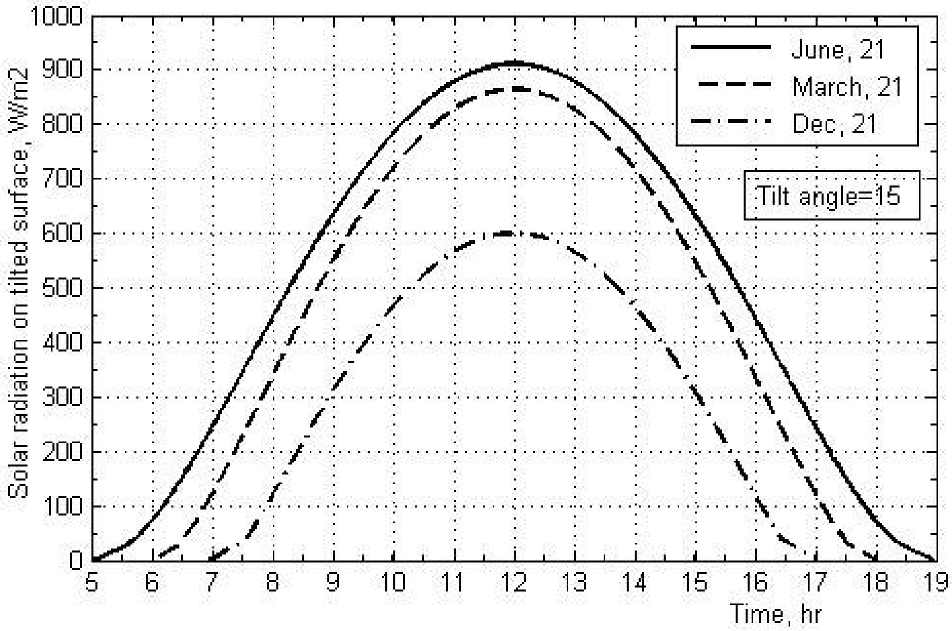

**Fig. 3. Global solar radiation intensity on a tilted surface (β =15°, Latitude=30° N).**

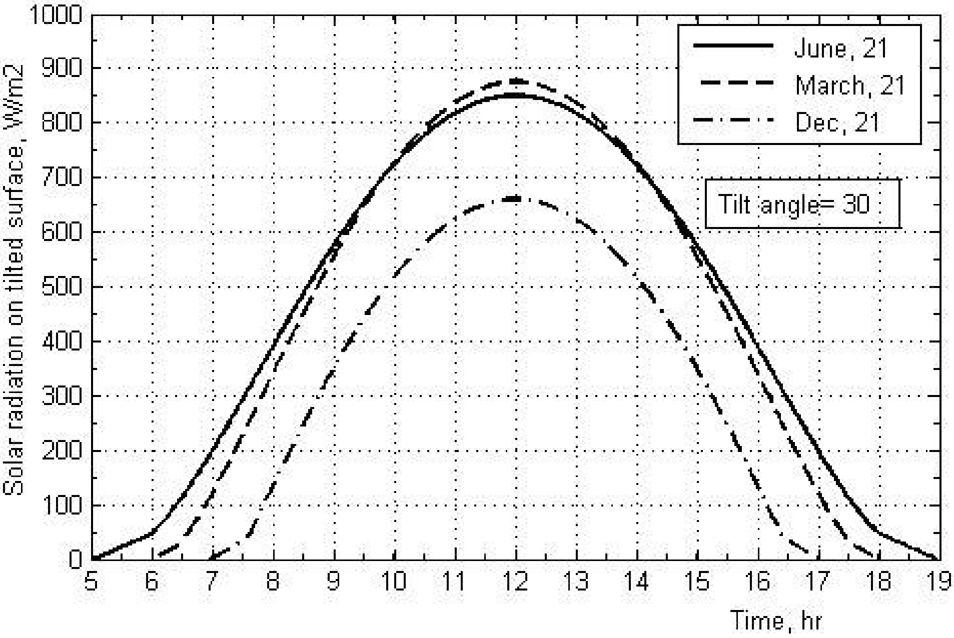

**Fig. 4. Global solar radiation intensity on a tilted surface (β =30°, Latitude=30° N).**

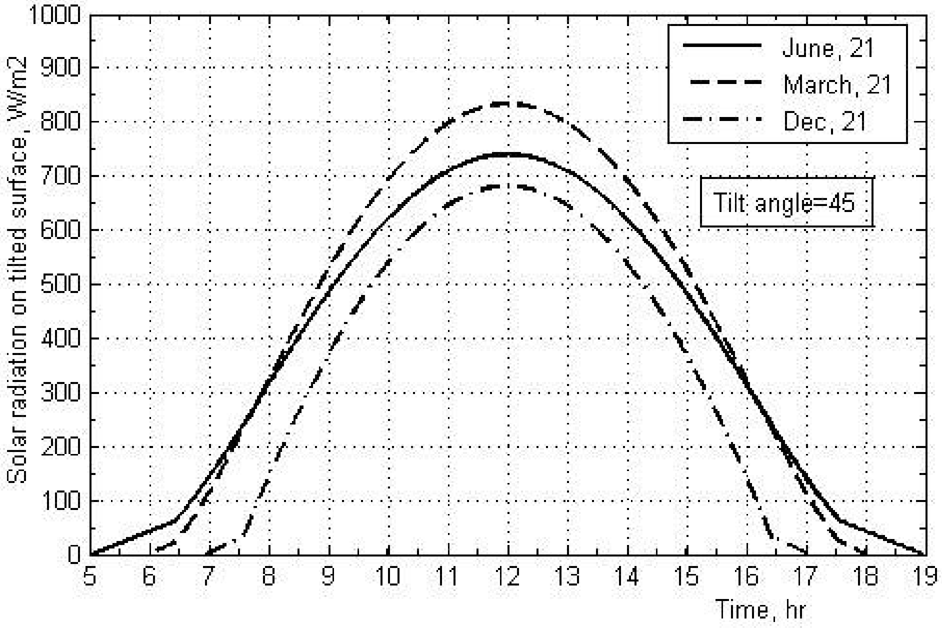

**Fig. 5. Global solar radiation intensity on a tilted surface (β =45°, Latitude=30° N).**

Equations from (13) to (21) are solved to predict the performance of a typical silicone PV cell. Results are shown in Fig. 6 as the I-V characteristics of the cell at different solar radiation intensities. The maximum power line is also plotted as a dashed line on the same figure.

Operating the system at maximum power condition, the cell current $I_m$, voltage $V_m$ and power $P_m$ (W) can be approximated from the best curve fitting as,

$$I_m = 0.0054162\, G_c + 0.0054702 \tag{23}$$

$$V_m = -3.0357\exp(-8)\, G_c^2 + 6.7929\exp(-5)\, G_c + 0.505 \tag{24}$$

$$P_m = 0.0025\, G_c - 0.02366 \tag{25}$$

The pumped water flow rate ($m^3/s$) can be calculated from,

$$Q = \frac{\eta_p\, n\, P_m}{\rho\, g\, h} \tag{26}$$

Where, n is the number of cells in the PV array (n = 4x72 in our case).

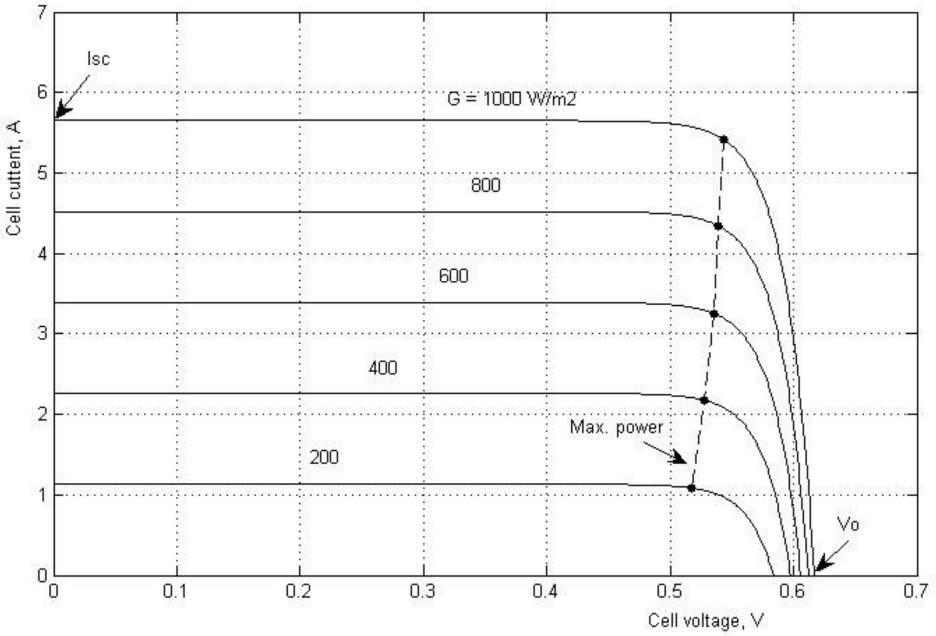

**Fig. 6. The I-V characteristics of the used silicone cell ($I_{sc}$ = 5.65 A and $V_o$ = 0.617 V)**

The main function of the pump controller is to switch on the pump when the current produced from the PV array is sufficient to operate the pump and switch off below this value. According to above equations, this current is directly proportional to the level of solar radiation. If the pump operation starts at a time ($t_1$) when the solar radiation intensity on the tilted surface of the PV array $G_c$ reaches a predetermined value ($G_{op}$) and shut down at ($t_2$) when $G_c$ goes below this value, the function of the pump controller can be expressed as,

$$\text{The pump is on if } G_c \geq G_{op} \text{ and is off when } G_c < G_{op} \tag{27}$$

Referring to equations (25) to (27), the daily amount of pumped water, $\overline{Q}$ ($m^3$/day) can be predicted by numerically integrating the above equation from $t_1$ to $t_2$ as,

$$\overline{Q} = \left(\frac{\eta_p\, n}{\rho\, g\, h}\right)\int_{t_1}^{t_2} (0.0025\, G_c - 0.02366)\, dt \tag{28}$$

Table 2 shows the values of $t_1$ and $t_2$ corresponding to $G_{op}$ values of 300, 400, and 500 W/$m^2$ on the PV array tilted surface. These results are obtained for 21th of March, June, September and December that represents the different seasons of the year. The corresponding operating time ($t_2$–$t_1$) is also given.

The predicted quantity of pumped water per day is given in Table 3 for the same days. These results are represented graphically in Fig. 7. The predicted quantity of pumped water per day is larger than the target value (8 $m^3$/day) all over the year with a minimum value at December, 21 ranging from 12.12 to 16.4 $m^3$/day corresponding to operating hours 4.15 and 8.79 per day respectively. In summer and equinoxes, daily pumped water is far larger than target as shown Table 3.

**Table 2. Pump on and off hours at different seasons and $G_{op}$ values.**

| $G_{op}$ | 300 W/m² | | | 400 W/m² | | | 500 W/m² | | |
|---|---|---|---|---|---|---|---|---|---|
| **Day** | $t_1$, hr | $t_2$, hr | $t_2 - t_1$ | $t_1$, hr | $t_2$, hr | $t_2 - t_1$ | $t_1$, hr | $t_2$, hr | $t_2 - t_1$ |
| **March, 21** | 7.82 | 16.18 | 8.36 | 8.29 | 15.72 | 7.43 | 8.76 | 15.24 | 6.48 |
| **June, 21** | 7.55 | 16.46 | 8.91 | 8.05 | 15.92 | 7.87 | 8.62 | 15.39 | 7.77 |
| **Sept., 21** | 7.82 | 16.18 | 8.36 | 8.29 | 15.72 | 7.43 | 8.76 | 15.24 | 6.48 |
| **Dec., 21** | 8.79 | 15.21 | 6.42 | 9.33 | 14.68 | 5.35 | 9.93 | 14.08 | 4.15 |

**Table 3. Quantity of pumped water per day at different seasons and $G_{op}$ values.**

| $G_{op}$ | 300 W/m² | 400 W/m² | 500 W/m² |
|---|---|---|---|
| **Day** | $\overline{Q}$, m³/day | $\overline{Q}$, m³/day | $\overline{Q}$, m³/day |
| **March, 21** | 24.21 | 23.10 | 21.47 |
| **June, 21** | 28.16 | 26.43 | 24.06 |
| **Sept., 21** | 24.21 | 23.10 | 21.47 |
| **Dec., 21** | 16.40 | 14.68 | 12.12 |

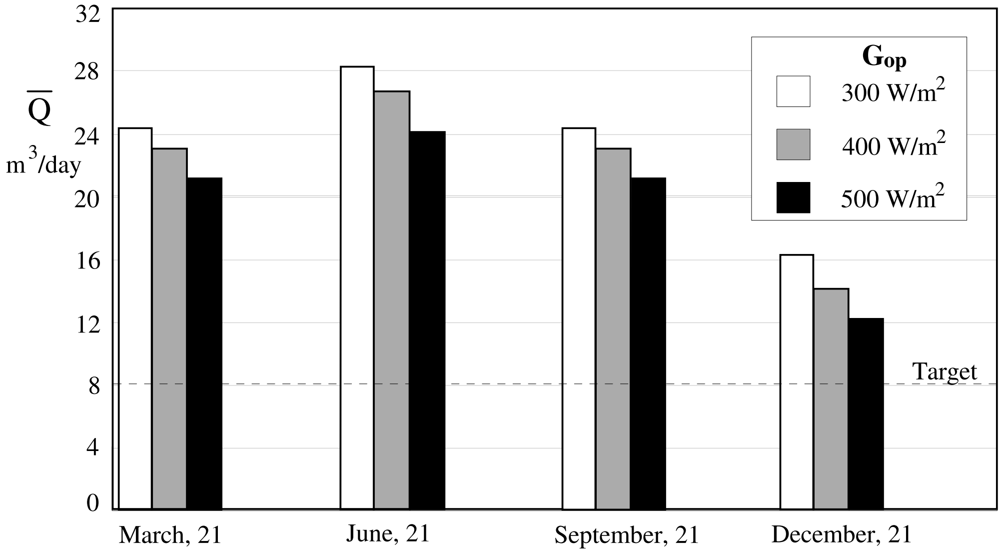

**Fig. 7. Quantity of pumped water per day at different seasons and $G_{op}$ values.**

The efficiency of the PV array is calculated as a function of time from equation (19) in the same days. Results have shown that the PV array efficiency is almost constant during the operating hours with minor changes between seasons. The predicted values of the PV array efficiency ranges from 13.86% in winter to 13.91% in summer solstice. These results are larger than that specified by the tender (13%).

The above results are predicted under clear sky and normal climatic conditions. The actual amount of daily pumped water is expected to be less than that due to occasional clouds and situations that may occur such as the drop in water level in the well and reaching the full tank level which are not considered. However, it is recommended to facilitate the system with a small size battery bank to store the excess solar energy in sunny days and these situations. This stored energy is useful in keeping smooth pump running in cloudy days and supplying lights in dark nights for those people.

## CONCLUSIONS

In this paper, a methodology is developed for performance perdition of a proposed direct coupled PV water pumping system in St. Catherine area, South Sinai, Egypt climate. The system consists of a four modules PV array (with 72 photovoltaic cells in each module), pump controller and a 12 VDC submerged pump. The target of the system is to supply at least 8 $m^3$ from the well at a total head 30-40 m. A computer simulation program is developed to predict the performance of the proposed system. This program uses models for solar radiation data, the PV array with three tilt positions all over the year. The model is adapted to simulate the hourly performance of the system at any day of the year, with three positions points PV array orientation. The pump controller characteristics are varied to achieve the best performance for the proposed system. Results which are given in graphical form, have shown that the system is capable of pumping 24.06, 21.47 and 12.12 $m^3$/day at in summer solstice, equinoxes and winter clear sky days respectively. The calculated PV array efficiency ranges from 13.86% in winter to 13.91% in summer solstice which is larger than that specified by the tender (13%).

## REFERENCES

1- Appelbaum J. and Bany J., “Performance analysis of DC motor photovoltaic converter system”, Solar Energy, 1979, 122:439–445.

2- Loxsom F. and Durongkaveroj P., “Estimating the performance of a photovoltaic pumping system”, Solar Energy, 1994, 52(2):215–219.

3- Hadj Arab A., Ait Driss B., Amimeur R. and Lorenzo E., “Photovoltaic systems sizing for Algeria”, Solar Energy, 1995, 54:99-104.

4- Saied M.M. and Jabori A., “Optimal solar array configuration and DC motor parameters for maximum annual output mechanical energy”, IEEE Trans Energy Convers., 1989, 4:449–465.

5- Firatoglu, Z.A. and B. Yesilata, “New approaches on the optimization of directly coupled PV pumping systems”, Solar Energy, 77 (2004) 81–93.

6- Duffie J.A. and Beckman W.A., “Solar engineering of thermal processes”, New York John Wiley & Sons Inc, 1991.

7- Meinel A. and Mainel M., Applied Solar Energy, An Introduction, Addison-Wesley, Reading, MA, 1976.

8- Markvart T., Ed., “Solar Electricity”, John Wiley & Sons, Chichester, U.K., 1994.

9- Kreith F. and Kreider J.F., “Principles of solar engineering”. McGraw-Hill, New York, 1978.
10- Collares-Pereira M. and Rabl A., “The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insulation values”, Solar Energy, 1979, 22(2):155–164.
11- Iqbal M., “An Introduction to Solar Radiation”, Academic Press, Ontario, 1983.
12- Roger A.M. and Jerry V., “Photovoltaic systems engineering” second edition, Taylor and Francis e-Library, 2005.
13- Green M., “Solar Cells: Operating principles, technology, and system applications”, Chap. 5, Prentice Hall, Englewood Cliffs, NJ, 85–102 (1982).
14- Eikelboom J. and Jansen M., “Characterization of PV modules of new generations”, ECN-C-00-067, Report to NOVEM Contract 146.230-016.1, Available at www.ecn.com (2000).
15- Markvart T. and Castaňer L., “Practical handbook of photovoltaics: fundamentals and applications”, Elsevier Science Ltd., Oxford, UK, 2003.