Using Photovoltaic Array for Solar Water Pumping in Toshka Region, Egypt

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ABSTRACT

Using photovoltaic (PV) array for water pumping systems in Toshka region, Egypt needs more attention to their sizing and performance prediction. In this work, a simple methodology is developed for sizing and performance prediction of the direct coupled PV water pumping system under Toshka climate conditions. The system consists of a PV array, pump controller and submerged pump. Battery bank and charge controller may be added for night lightening. For this reason, a MATrix LABoratory (MATLAB) computer simulation program is developed to solve the system governing equations and predict its performance at different design and operating parameters. The program uses models for solar radiation data, the PV array with different tilt angles and tracking schemes. Solar radiation obtained from the theoretical model is compared with that obtained from the National Aeronautics and Space Administration (NASA) website. The model is adapted to simulate the hourly system performance at any day of the year, under different PV array orientation. The pump controller characteristics are also varied to achieve the best performance of the system. Results which are given in graphical form and simple correlations, have shown that the seasonal and optimum tilt tracking schemes are the most suitable for the PV array. Results are given also for specific system design parameters per unit area of the PV array. For any other specified design and operating parameters results can be easily obtained.

Keywords: photovoltaic, Solar Pumping, Toshka, Egypt

1. INTRODUCTION

Toshka project is designed to create a second Nile valley in the south of the Western Desert as shown in the map, Fig.1. It adds 540,000 feddans to the cultivated area and is irrigated by Nile waters via El-Sheikh Zayed canal which quota is around 5.5 billion cubic meters per year. It comprises various economic activities with a total investment cost of around 4.1 billion LE. The Nile River flows out of Lake Nasser, created by the Aswan High Dam. This lake is 550 km long and 35 km across at its widest point. It covers a total surface area of 5250 km^2 in Egypt and Sudan and has a storage capacity of 157 km^3 of water. The reservoir of Toshka Lakes is created from water drained from Lake Nasser in order to control its water level. This water is also used to irrigate crops in this region-here, some circular fields can be seen between Lake Nasser and the Toshka Lake located furthest eastward.

Fig. 1 A map of Toshka region.

The water is taken from Lake Nasser, behind the Aswan High Dam, and pumped by a huge pump (Mubarak) station through a series of canals into the desert, thereby allowing for irrigated agriculture. The results collected by Taha et al [1] shows that the depth to the main water aquifer, represented by saturated Nubian sandstone, ranges from 80 to 100 m.

Thus, the main source of fresh water for domestic use and agriculture activities in Toshka region is the ground water. In this place in Egypt, abundant ground water and solar radiation exist. In these remote areas, people use diesel engines to supply power for pumping water from wells. Sometimes, the approach roads to get the diesel fuel and spare parts are difficult. The problem is getting more worth with the latest increase in the fuel cost and the need for decreasing the air pollution and green house gases in the Earth's atmosphere. Solar water pumping systems usually use PV arrays to convert solar radiation into electric direct current to facilitate the wells with these green energy systems.

The use of PV array to supply these systems with power is the preferred choice, especially where there is adequate solar resource and large water demand. Several experimental researches and theoretical analyses of these pumping systems have been published. The direct coupled PV array 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 performance of the PV array water pumping system has been studied with different modeling techniques, and the optimal solar array configurations are tested [2]-[6]. The direct coupled system has been also studied experimentally and analyzed under steady state conditions [4]-[6].

As shown in Fig. 2, the direct coupled solar water pumping system consists basically of a PV array, pump controller and a submerged pump. The system may also contain a suitable battery bank and a solar charge controller to regulate and insure power supply to the submerged pump in cloud sky condition and provide light at dark nights. 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 conditions for more than 2-3 minutes. The pump is also switched off when the water level in the storage tank reaches a certain level and the tank is full.

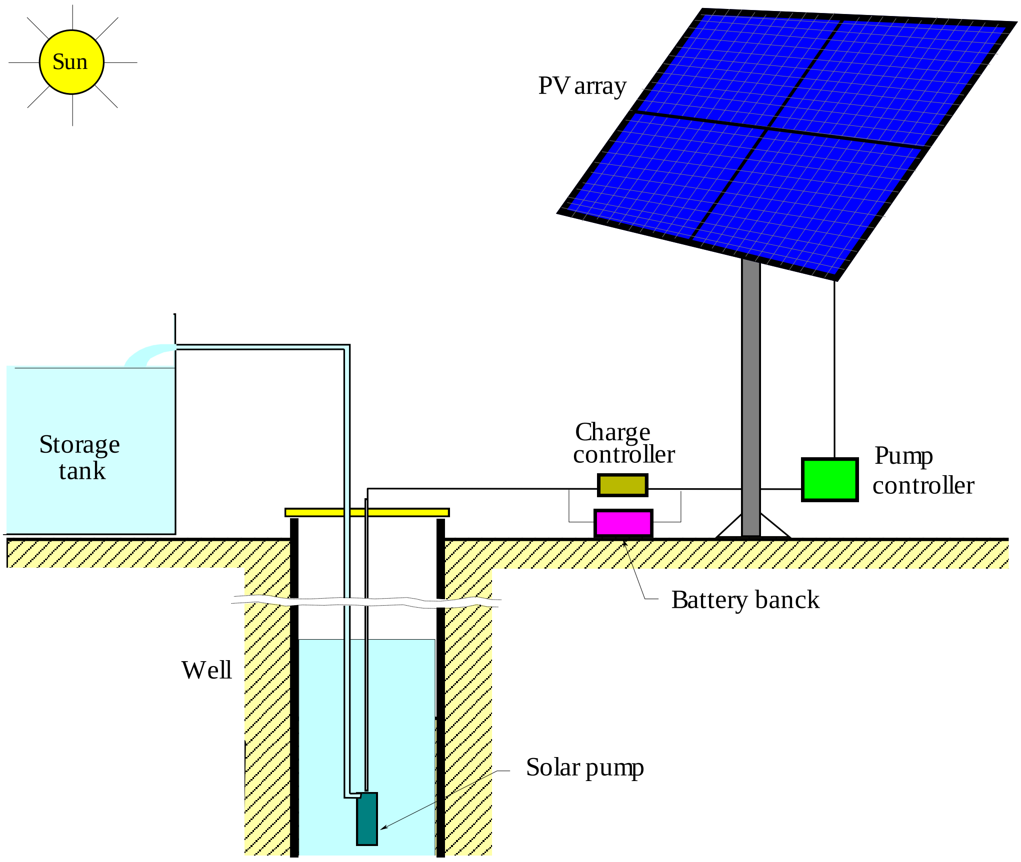

Fig. 2 Schematic diagram of the direct coupled PV solar water pumping system.

Practically, the PV array consists of a number of modules connected in series / parallel to produce the necessary direct current voltage. Usually, this voltage is a multiple of 12 DCV. Each module contains a number of photovoltaic cells that convert the falling solar isolation into a direct current. The function of the pumping system is to supply a certain daily amount of fresh water all over the year to a storage tank just over the ground level near the well.

2. SYTEM MODELING

The modeling of the PV array water pumping system includes the solar radiation, PV array and the pump. The pump controller function is also taken into consideration.

Solar Radiation

The design and sizing of the PV pumping system depend mainly on the solar radiation since the produced power depends on its value. The global solar radiation intensity on the PV array tilted surface, G_c can be calculated from Duffie and Beckman [7] (neglecting the reflection component) as,

$$G_c = R_b B_h + cos^2\left(\frac{\beta}{2}\right) D_h \quad (1)$$

Where, B_h and D_h are the beam and diffuse solar radiation components on horizontal surface respectively,
β is the PV array tilt angle,
and R_b is the beam radiation tilt factor given by,

$$R_b = \frac{\cos(L-\beta)\cos\delta\cos h + \sin(L-\beta)\sin\delta}{\cos L\cos\delta\sin h + \sin L\sin\delta} \quad (2)$$

Where, L is the latitude angle of Toshka, L = 23.45^o N.
h is the solar hour angle,

$$h = (12 - t) \times 15^o \quad (3)$$

t is the local time, hours,
δ is the solar declination angle defined by,

$$\delta = 23.5\ sin\left[\frac{360}{365}(N + 284)\right] \quad (4)$$

and N is the day number starting from January first.

The total solar radiation intensity on a horizontal surface G_h is obtained from the clear sky model as,

$$G_h = k_{td}\, G_{oh} \quad (5)$$

Where, G_{oh} is the extraterrestrial irradiance on a horizontal surface given by as,

$$G_{oh} = G_{sc}\, \varepsilon\, (cos\, L\, cos\, \delta\, cos\, h + sin\, L\, sin\, \delta) \quad (6)$$

Where, $$\varepsilon = \left[1 + 0.033 cos\left(\frac{2\pi N}{365}\right)\right] \quad (7)$$

and G_{sc} is the solar constant (1367 W/m^2).

The daily average clearness index obtained from NASA website [8] for Toshka region over 10 years and can be expressed to a good accuracy as a function of N by the polynomial,

$$k_{td} = 4.5753^{-9}\ N^3 - 4.2009^{-6}\ N^2 + 0.0009185\ N + 0.66893 \quad (8)$$

The ratio, r_d of diffuse irradiance on a horizontal surface, D_h to the daily diffuse irradiation, $\overline{D}_h$ can be estimated by Collares-Pereira and Rabl [9] as,

$$r_d = \frac{D_h}{\overline{D}_h} = \frac{G_{oh}}{\overline{G}_{oh}} \tag{9}$$

$\overline{G}_{oh}$ is the daily extraterrestrial solar radiation on a horizontal surface, obtained by integrating equation (6) over the day.

$\overline{D}_h$ can be obtained in terms k_{td} as,

$$\overline{D}_h = F_d\, \overline{G}_h \tag{10}$$

Where,

$$F_d = 1.88 - 2.272\, k_{td} + 9.473\, k_{td}^2 + 21.856\, k_{td}^3 + 14.648\, k_{td}^4 \qquad = 0.99 \quad if \quad k_{td} \;\le\; 0.17 \tag{11}$$

Then, the hourly diffuse solar radiation can be obtained from equation (9) as,

$$D_h = r_d\, \overline{D}_h \tag{12}$$

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

$$B_h = G_h - D_h \tag{13}$$

As the diffuse and beam solar radiation components on horizontal surface (D_h and B_h) are obtained from equation (12) and (13) respectively, the global solar radiation intensity on tilted PV array surface, G_c can be obtained as a function of time for any day of the year from equation (1).

Tracking Scheme of the PV Array

To attain maximum utilization of solar radiation, full-tracking should be used for the PV array. But this will results in a significantly higher cost. South facing with a fixed tilt angle equal to the latitude angle of the place, L yields a maximum output all over the year, Duffie and Beckman [7]. System with (L) tilt angle produces a maximum output in equinoxes. If the tilt angle is adjusted to (L-15^o), the system will produce a maximum output in summer, while a tilt of (L+15^o) yields a maximum output in winter season. The slope of the PV array can be adjusted manually once each month. This approach has been considered in some previous studies, but the frequency of tilt adjusting is seen to be much bothering for those simple people. However, all tracking schemes are discussed in the present work, under Toshka climate conditions.

Photovoltaic Array Modeling

There are many types of PV cells in the international market; the best of which is the silicon mono crystalline type. The efficiency of this cell type reaches 17.5%. Therefore, it is chosen for this research work. The I-V characteristic equation of the photovoltaic cell is given by Roger and Jerry [10] as,

$$I = I_L - I_o \left[exp\left(\frac{qV}{kT}\right) - 1 \right] \tag{14}$$

Where, I_L is the cell (light) current which is equal to the short circuit current ($V=0$),

I_o is the reverse saturation (dark) current, A

q = 1.6x10^{-19} Coul

k = 1.38× 10^{-23} J/K

and T is the cell temperature, K

The I-V performance of the cell is sensitive to the operating temperature, T. The open circuit voltage of a silicon cell decreases approximately by 0.5% /C as reported by Eikelboom and Jansen [11]. 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 can be estimated quite accurately according to Ross [12] as,

$$T = T_a + \frac{T_N - 20}{800} G_c \tag{15}$$

Where, T_a is the ambient air temperature, C
and T_N is the nominal operating cell temperature, C.
T_N is the PV cell temperature that is reached when the cell is operated at no load condition in an ambient air temperature 20 C, air mass ratio 1.5, irradiance 800 W/m^2 and a wind speed less than 1 m/s. The value of T_N varies from about 42 to 46 C, and can be experimentally measured. In this analysis, the value of T_N is assumed by Ross Jnr and Smokler [13].as,

$$T_N = T - T_a + (0.035) G_c \tag{16}$$

The monthly average ambient air temperature at 10 m above sea level in Toshka region over ten years is given in Table (1) as obtained from the NASA website [8].

Table 1 Monthly averaged air temperature at 10 m above sea level in Toshka (°C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	15.37	17.11	22.14	26.29	30.16	34.97	33.83	33.10	32.44	27.64	19.03	16.39
2005	13.90	18.46	19.94	24.89	28.22	30.69	31.87	32.27	30.07	25.77	18.76	18.18
1995 - 2005	14.91	16.50	20.04	25.40	30.00	31.03	32.14	32.31	30.77	26.64	20.88	16.17

To determine I_o, the current, I in equation (14) is set to zero. In this case, V is equal to the open circuit voltage, V_o, yielding the result:

$$V_o = \left(\frac{kT}{q}\right) Ln \frac{I_L + I_o}{I_o} \cong \left(\frac{kT}{q}\right) Ln \frac{I_L}{I_o} \tag{17}$$

since $I_L >> I_o$

$$I_o = I_L \exp\left(-\frac{qV_o}{kT}\right) \tag{18}$$

Since the cell light current, I_L is directly proportional to the cell irradiance, the value of $I_L(G)$ at any other irradiance, $I_L(G)$ is given by,

$$I_L(G) = \left(\frac{G}{G_s}\right) I_L(G_s) \tag{19}$$

Where, $I_L(G_s)$ is known under the standard conditions of; G_s = 1000 W/m^2 at 1.5 air mass ratio and 25 C. From the manufactures catalogues of a typical silicon mono crystalline PV cell, the value of $I_L(G_s)$ is 5.65 A and V_o = 0.617 V.
The above equations can be solved to obtain V and I produced by the photovoltaic cell at different operating conditions.
The power output of the cell, P is given by,

$$P = F\, I\, V \tag{20}$$

Where, F is the cell fill factor which is a measure of its quality (0.5 to 0.82). An empirical expression for the fill factor is given by Green, [14] as,

$$F = \frac{V_o - (kT/q)Ln\left(qV_o / kT + 0.72\right)}{V_o + kT/q} \tag{21}$$

Solving equations from (14) to (21), the output current and voltage from the PV array can be obtained as a function of day time.

Modeling of the Pump

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

$$P_p = n\,A\,P = \rho\,g\,H\,Q/\eta_p \tag{22}$$

Where, H is the total head, Q is the pump flow rate (m^3/hr), n is the number of cells in one square meter of the PV array, A is the array area and η_p is the pump overall efficiency.

3. RESULTS AND DISCUSSION

A computer program using MATLAB (version 7.0) is developed and employed to solve the above equations for any PV array tilt angle, either fixed, tilt angles or working on any tracking scheme. The intensity of global solar radiation on a horizontal surface, G_h for Toshka region is obtained as a function of time (with a time step of 0.01 hour) using equations from (1) to (13). These results can be obtained for any day of the year.

The daily global solar radiation on 1 m^2 horizontal surfaces is obtained for any day of the year by integration from sunrise to sunset with the same time step. Results for all days of the year are presented in Fig. 3. For horizontal surface, a maximum value (summer solstice 21 June) is 8.12 kWh/m^2.day, minimum value (winter solstice 21 December) is 4.4 kWh/m^2.day, while for the equinoxes (21 March/September) it is 6.92 kWh/m^2.day.

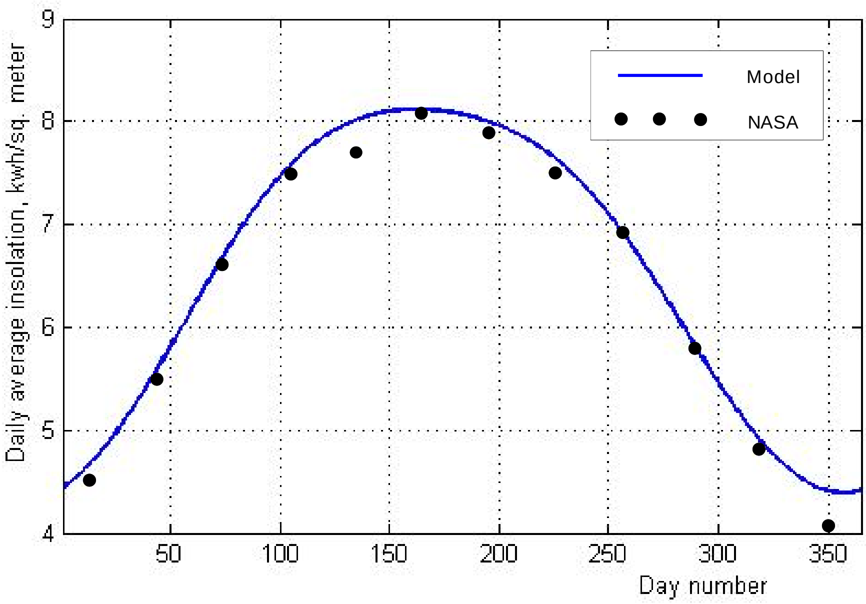

Fig. 3 Daily global solar radiation on horizontal surface at Toshka region.

Table (2) shows the results for horizontal surface in the years 1995 and 2005 as obtained from NASA website. The monthly average global solar radiation intensity on horizontal surface at Toshka region over 10 years is also given and plotted in Fig. 3. It is clear from the figure that results extracted from the model are close to that obtained from NASA website, which proves the validation of the present mathematical model.

Table 2 Monthly averaged insolation incident on a horizontal surface (kWh/m^2/day)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	4.05	5.39	6.49	7.16	7.62	8.00	7.82	7.43	6.87	5.81	4.48	4.04
2005	4.43	5.40	6.58	7.48	7.92	7.81	7.73	7.47	6.88	6.07	5.07	3.84
1995 - 2005	4.39	5.42	6.57	7.40	7.69	8.03	7.85	7.36	6.88	5.80	4.80	3.98

Fixed PV array

The optimum tilt angles for summer solstice, equinoxes and winter solstice respectively reported by Duffie and Beckman [7] are considered. These angles are; south facing PV array with tilt angles (L-15^o), (L) and ($L+15^o$) respectively. Results for these tilt angles are shown in Fig. 4. This system is suitable for people that require a maximum output at a certain season of the year. For maximum output in summer, an array tilt angle (L-15^o) can be used, while for winter, the tilt angle ($L+15^o$) is better as shown in Fig 4. However, the array tilt angle (L) results give intermediate output most of the year, and it is a good option to the whole year fixed angle system.

Sun Tracking PV array

The tracking schemes used in practice for the PV array are;

1- Full tracking, in which the PV array surface follows the sun motion, such that the beam solar radiation is always normal to the array surface. This scheme needs a heliostat system which is costly and is only suitable for large installations.

2- Monthly tracking, in which the tilt angle is adjusted manually each month with keeping the surface facing south. This scheme is bothering for simple people and is not considered here.

3- Seasonal tracking is similar to the monthly, but the tilt angle is adjusted four times corresponding to the four seasons. This tracking scheme as shown in Fig. 5 by a dashed line shows maximum results in solstices and equinoxes.

4- Optimum tilt tracking in which the tilt is adjusting to takes the path of maximum value of G_c as shown in Fig. 5 by continuous line. A summary of the proposed tracking schemes is given in Table (3), while a summary of all corresponding results is presented in Table (4). It is to be noted that the asymmetry in results shown in Figs. 4 and 5 are due to that in the values of k_{td}.

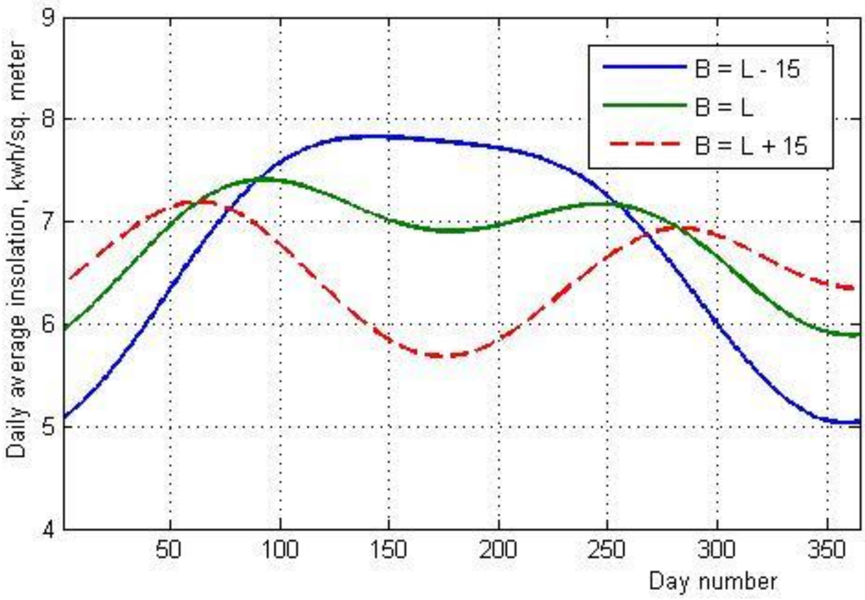

Fig. 4 Daily global solar radiation on different array tilt angles at Toshka region.

Table (3) Proposed tracking schemes for the PV array in Toshka region.

Tracking scheme	**Description**					
Monthly tracking	*N*	Tracking step each month				
	β	From 7.5^o at 21 June (with a step 2.5^o per month) to 37.5^o				
Seasonal tracking	*N*	1 - 35	36 - 126	127 - 218	219 - 310	311 - 365
	β	*L*-15	*L*	*L*+15	*L*	*L*-15
Optimum tilt tracking	*N*	1 - 65	66 - 91	92 - 255	256 - 282	283 - 365
	β	*L*-15	*L*	*L*+15	*L*	*L*-15

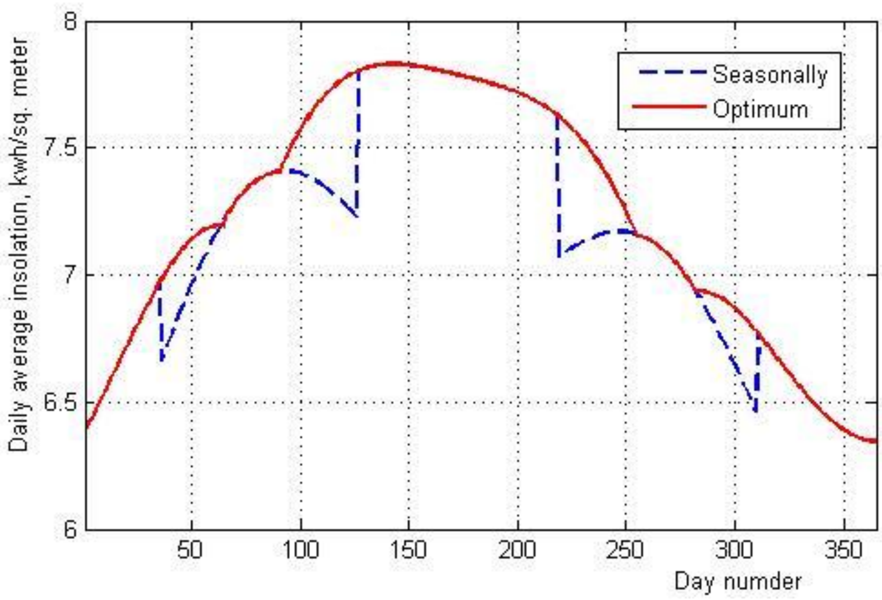

Fig. 5 Daily global solar radiation for different tracking schemes at Toshka region.

Table (4) Daily global solar radiation in Toshka region for different fixed, and tracking tilt angles

Array tilt angle, degrees	**Daily global solar radiation**, ($\bar{G}_c$) kwh/m^2.day		
	Maximum	**Minimum**	**Average value**
L-15^o (fixed)	7.45	3.87	6.20
L (fixed)	6.97	4.43	6.19
L+15^o (fixed)	6.69	4.72	5.80
Seasonal tracking	7.45	4.72	6.49
Optimum tilt tracking	7.45	4.72	6.57

The average solar radiation intensity on the array surface is considerably higher for the tracking schemes than that for fixed array as shown in Figs. 4 and 5 and Table (4). The optimum tilt tracking is seen to be best the choice. However, the results of the two tracking schemes are close. The seasonal and optimum tilt tracking are the most suitable tracking schemes for simple people, since they need less adjusting all over the year, not like that of monthly which need 12 tilt adjusting per year.

Equations from (14) to (21) are solved to predict the performance of a typical mono crystalline silicone photovoltaic cell. The above results are used as input data to solve the governing equations for the PV array. Figure 6 shows the results of this cell given as the *I-V* characteristics of the cell at different solar radiation intensities (from 200 to 1000 W/m^2). The figure also shows the maximum power line. Usually, the PV array system operates at maximum power condition. The cell current I_m, voltage V_m and power P_m (W) at this condition can be correlated as a function of G_c (W/m^2) from the best curve fitting as,

$$I_m = 0.0054\ G_c + 0.0162 \tag{23}$$

$$V_m = -3.57^{-8}\ G_c^2 + 7.09^{-5}\ G_c + 0.5 \tag{24}$$

$$P_m = I_m\ V_m = 0.0024 G_c + 0.0022 \tag{25}$$

The water flow rate of the pump per unit array area, $q = Q/A$ depends on the produced power, and can be calculated from,

$$q = \frac{\eta_p\ n\ P_m}{\rho\ g\ H} \tag{26}$$

Where, n is the number of cells per unit array area,
H is the total head of the water in the well,
and η_p is the pump efficiency.

The Pump Controller

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

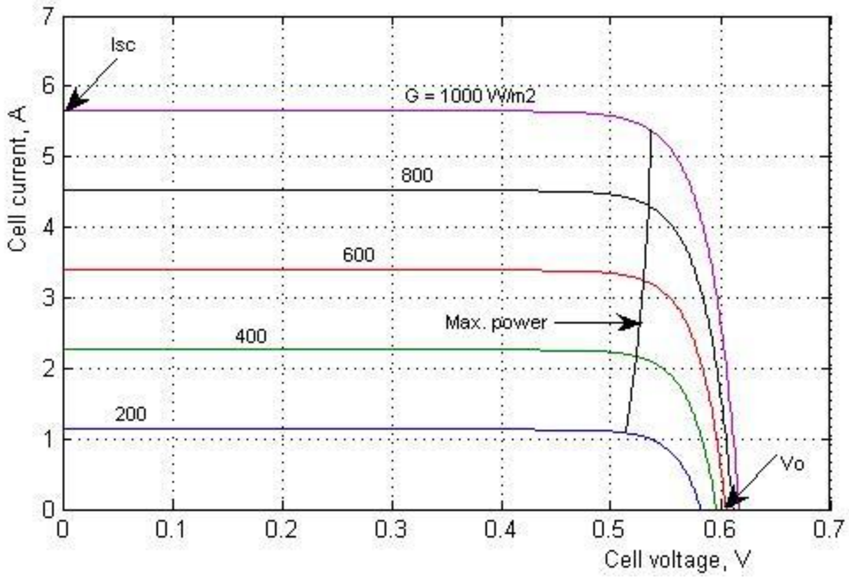

Fig. 6 Characteristics of a typical mono crystalline silicone cell.

Pump is on if $G_c \geq G_{op}$ and is off when $G_c < G_{op}$ (27)

Referring to equations (26) and (27), the daily amount of pumped water per unit array surface area, $\bar{q}$ (m^3/m^2.day) can be obtained by numerical integration of equation (26) over the operating period (from t_1 to t_2 with a time step 0.01 hours) as,

$$\bar{q} = \left(\frac{\eta_p \, n}{\rho \, g \, H} \right) \left[0.0024 \, \bar{G}_c + 0.0022 \, \Delta t \right] \quad (28)$$

Where, $\bar{G}_c$ is the daily global solar radiation on 1 m^2 of the array surface during the operation period ($\Delta t = t_2 - t_1$).

The first term $(\eta_p \, n/\rho \, g \, H)$ in equation (28) is a system design parameter that depends on H, n and η_p. The following results are obtained for a typical values of $n=50$, $\eta_p=90\%$ *and* $H=50$ *m*. The function of the pump controller is decided according to the pump characteristics and the hourly solar radiation, G_c each day. The hourly variation of G_c on the array surface for solstices days (21 June/ December) and equinoxes days (21 March/September) of the year at the corresponding optimal tilt angles. 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 surface are obtained and presented in Table (5). The operating periods (Δt) and the integrated total solar radiation during this period over one square $\bar{G}_c$ (kWh/m^2 day) are also given.

The predicted quantity of daily pumped water $\bar{q}$ (m^3/day) is given in Table (6) for the same days. These results are represented graphically in Fig. 7. The quantity of daily pumped water, for 1 m^2 array area, over the year is minimum at December 21 ranging from 4.30 to. 4.83 m^3/day corresponding to G_{op} values of 500 and 300 W/m^2 respectively. In summer, the daily pumped water is larger from 5.22 to 5.82 m^3/day as shown in Table (6) and Fig. 7.

Usually, these systems are designed under the worst conditions which are around winter solstice day, 21 December. The area of the PV array can be decided according to the required total quantity of daily water demand and the pump power can be determined from equation (22).

Table (5) Operation periods at different seasons and G_{op} values

G_{op}	300 W/m^2				400 W/m^2				500 W/m^2			
Day	t_1,	t_2,	Δt	$\bar{G}_c$	t_1,	t_2,	Δt	$\bar{G}_c$	t_1,	t_2,	Δt	$\bar{G}_c$
March, 21	7.2	16.8	9.6	7.028	7.6	16.4	9	6.751	8.1	15.9	7.8	6.301
June, 21	6.9	17.1	10.2	7.357	7.4	16.6	9.2	7.000	7.9	16.2	8.3	6.592
Sept., 21	7.3	16.8	9.5	6.754	7.7	16.3	8.6	6.438	8.2	15.8	7.6	5.983
Dec., 21	7.5	16.5	9.0	6.098	7.8	16.2	8.4	5.885	8.3	15.7	7.4	5.433

Table (6) Quantity of pumped water per day at different seasons and G_{op} values

G_{op} (W/m^2)	300	400	500
Day	$\bar{q}$, m^3/day		
March, 21	5.5637	5.3448	4.9889
June, 21	5.8238	5.5422	5.2188
Sept., 21	5.3464	5.0971	4.7366
December, 21	4.8272	4.6583	4.3012

The results of this research are obtained under specific assumptions of η_p, n and H. Clear sky and normal climatic conditions of Toshka region are also assumed. 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 suitable battery bank and charge controller to store the excess solar energy in sunny days. This stored energy is useful in keeping a smooth pump running in cloudy days and supplying lights in dark nights for those people.

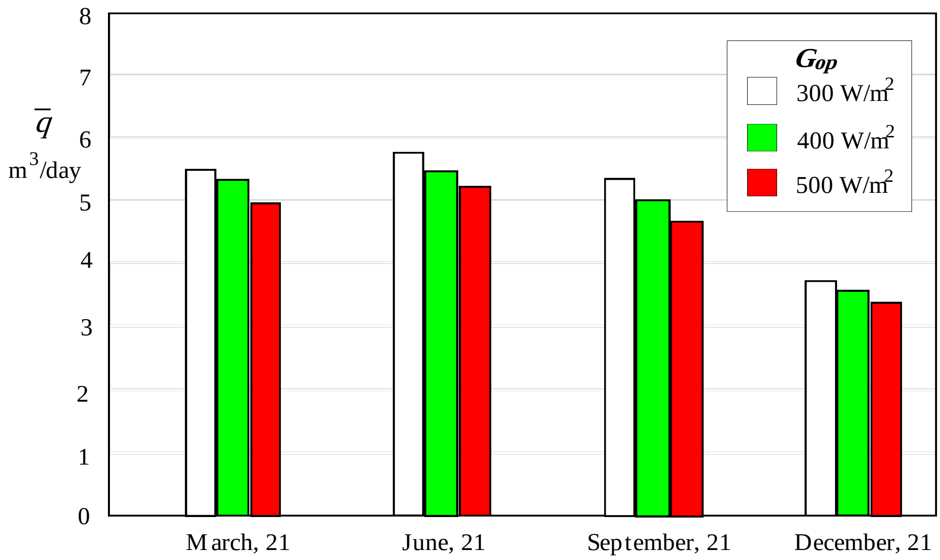

Fig. 7 Daily pumped water per unit array area at different seasons and G_{op} values

4. CONCLUSIONS

In the present work, a methodology for sizing and performance prediction of the direct coupled PV water pumping system at Toshka, Egypt is developed. The system consists mainly of a PV array, pump controller, battery bank, charge controller and a DC submerged pump. A computer program using MATLAB (version 7.0) for sizing and performance prediction of the system is developed. This program uses models for solar radiation, the PV array with different fixed, tilt angles and tracking schemes. The pump controller characteristics are also considered. Results which are given in graphical form and a simple equations have shown The daily global solar radiation on 1 m^2 horizontal surfaces is obtained for any day of the year, a maximum value (summer solstice 21 June) is 8.12 kWh/m^2.day, minimum value (winter solstice 21 December) is 4.4 kWh/m^2.day, while for the equinoxes (21 March/September) it is 6.92 kWh/m^2.day. The optimum tilt angles for summer solstice, equinoxes and winter solstice are; south facing PV array with tilt angles (L-15^o), (L) and (L+15^o) respectively. This system is suitable for people that require a maximum output at a certain season of the year. However, the array tilt angle (L) is a good option to the whole year fixed angle system. Moreover, The seasonal and optimum tilt tracking are the most suitable tracking schemes for simple people, since they need less adjusting all over the year, not like that of monthly which need 12 tilt adjusting per year.

Results which are given also in graphical form and a simple equations have shown the daily pumped water per unit array area with specific deign parameters and different pump controller on/off settings. Results have shown that the seasonal and optimum tilt tracking schemes are the most suitable for the PV array. For a total head of 50 m, number of cells per unit array area 50, overall pump efficiency 90 % and pump controller adjusted at 300 W/m^2, the system is capable of pumping 5.82 and 4.83 m^3/day per unit array area in summer and winter solstices days respectively. Different values are obtained for higher pump controller on/off characteristics (400 and 500 W/m^2).Then, these systems are designed under the worst conditions which are around winter solstice day, 21 December In addition, the area of the PV array can be decided according to the required total quantity of daily water demand and the pump power. Moreover, results for different design parameters can also be easily obtained. However, it is recommended to facilitate the system with a suitable battery bank and charge controller to store the excess solar energy in sunny days. This stored energy is useful in keeping a smooth pump running in cloudy days and supplying lights in dark nights for those people.

5. NOMENCLATURE

A	PV array area (m^2)
B	Beam solar radiation intensity (W/m^2)
B_h	The hourly beam solar irradiance (W/m^2)
D	Diffuse (sky) solar radiation intensity (W/m^2)
D_h	The daily diffuse irradiation on horizontal surface (W/m^2)
F	Photovoltaic cell fill factor
G	Global (total) solar radiation intensity (W/m^2)

G_c Global solar radiation intensity on the PV array tilted surface (W/m^2)
$\overline{G}_c$ Daily global solar radiation on 1 m^2 of the array surface during the operation period ($\Delta t = t_2 - t_1$).
G_{oh} Extraterrestrial irradiance on a horizontal surface (W/m^2)
$\overline{G}_{oh}$ Daily extraterrestrial solar radiation on a horizontal surface (W/m^2)
G_{op} Operating period level of solar radiation (W/m^2)
G_{sc} Solar constant (1367 W/m^2)
g Gravity acceleration, (m/s^2)
H Total head of the water in the well (m)
h Solar hour angle
I Current (A)
I_L Cell (light) current which is equal to the short circuit current ($V=0$)
I_m Cell current (A)
I_o The reverse saturation (dark) current (A)
k_{td} Daily average clearness index
L Latitude angle of the place (23.45^o N. for Toshka region)
N The day number starting from January first
n Number of cells in 1 m^2 of the PV array
P, P_p Cell output and pump power (W) respectively
Q, q Pump flow rate (m^3/s) and pump flow rate per unit area of PV array respectively ($Q = q\,A$)
$\overline{q}$ Predicted quantity of daily pumped water (m^3/day)
R_b Tilt factors for beam solar radiation intensity
r_d The ratio of diffuse irradiance on a horizontal surface
T Temperature (C)
T_a Ambient air temperature (C)
T_N Nominal operating cell temperature, (C)
t Local time (h)
V Voltage (V)

Subscripts

c Tilted surface of the PV array
d Daily
h Horizontal
m Maximum power
o Outside the atmosphere

Greek symbols

β PV array tilt angle
Δt Operating periods
δ Solar declination angle
η_p Pump overall efficiency

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