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PERFORMANCE OF SMALL SCALE SPV- POWERED-DRIP IRRIGATION SYSTEM FOR REMOTE REGIONS

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ABSTRACT

Water pumping for domestic use and irrigation purposes can be considered as one of the basic needs in the rural areas of Egypt. For the favor or remote conditions in the country, solar water pumping may be an alternative aspect of traditional driven pumps for remote areas. This paper presents a performance of photovoltaic-powered small scale drip irrigation system under Egyptian conditions. Electrical power outputs and hydraulic analysis of a submersible pump versus total operating water heads (2, 2.5, 3, 3.5, 4 & 4.5 m) and PV array sizes (2, 3 & 4 modules) were conducted during winter season 2005/2006. Results revealed that, the average output daily power ranged from 65.46 to 124.55 W and average daily array conversion efficiency were 11.38, 11.22 and 10.83% for modules 2, 3 and 4, respectively. Increasing of pumping head from 2 to 4.5 m causes an increase in the hydraulic power by 46.62, 73.04 and 75.08% for modules 2, 3 and 4, respectively, in case of fitted drip system. The cost annuity per equivalent hydraulic energy unit was 6.93 LE/104 m^4 for built-in (GR) fitted drip system at 4.5 m operating head. Operation of such systems in Egypt has demonstrated that energy generating components work for almost the entire life of the unit with little maintenance in comparison to conventional power generators.

Keywords: Solar photovoltaic, drip irrigation, equivalent hydraulic energy, PV efficiency, emission uniformity.

INTRODUCTION

Sun is one of the ever green energy sources that produce neither green house effect gases nor hazardous impact through its utilization. Renewable energy sources are being increasingly implemented in

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many applications due to the growing concern of environmental conservation. Egypt is endowed with a significant amount of renewable energy resources, as solar and wind, that they have been used commercially while the use of the other renewable resources is still in the research-and-development phases.

Photovoltaic (PV) water pumping has become a widely adopted solar energy technology in the last two decades (Firatoglu and Yesilata, 2004, and Awady et al., 2002). According to a World Bank report, ten thousand PV water pumping systems were installed worldwide up to the year 1993 (Barlow et al., 1993). This grew over sixty thousand systems by 1998 (Short and Oldach, 2003). PV water pumping systems have been considered as attractive means of providing water in remote locations since the majority of global rural population live in sunny tropical or sub-tropical areas (IT Power, 1984). PV systems are particularly useful in areas which are not practical to extend electricity grid, even in locations where connection could be made to a grid, utilities have found it more viable to use PV pumps than to extend and maintain the electric grid (Kou et al., 1998).A major advantage of PV pumping systems is that they are naturally matched with solar radiation as usually water demand increases during summer when solar radiation is in a maximum values (Anis and Metwally, 1994, and Awady et al., 2002). A directly coupled PV pumping system is composed of a PV array directly connected to a DC motor driving a centrifugal pump; however, it is certainly the cheapest, simplest, and most reliable of the other PV pumping techniques. The system simply stores water instead of storing electrical energy. The advantages of this system led to its widespread use all over the world. A good literature survey can be found in Anis and Metwally (1994). More recent results and analysis could be found in Akbaba et al., (1998) and Narvarte et al. (2000).

Anis et al. (1985) reported that a load composed of a DC motor driving a centrifugal pump represents a non-matched load to PV array. This is because the motor driving a volumetric pump requires an almost constant current for a given head, apart from the starting current, which tends to be higher. This condition does not match the PV array characteristics where the current varies almost in a linearly proportional with solar irradiance.

Experience of operating PV pumps has shown that due to their simplicity, high reliability and the stand-alone operation these systems are appropriate for remote areas (Barlow et al., 1993). Furthermore, PV pumps avoid uncertainties associated with fluctuating availability and price of Diesel fuel. Problems associated with fuel oil such as depletion of fossil fuel reserves, CO_2 emissions and pollution do not apply. The increasing shortage of fuel and the high cost of transmission of electrical power have motivated many countries to explore the possibilities of using alternate and renewable sources of energy in agriculture. Diesel pumps require continuous distribution of fuel oil, lubricants and spare parts to, often, remote locations, in addition to requiring trained operators and technicians. Experience has shown that once installed properly, PV pumps only need minimal attendance and often work unattended for long periods of time.

Hafner and Moarotz (1991) sid that in regad to the use of solar power systems for irrigation facilities, there are various possibilities for usage ranging from micro-irrigation systems with as little as 100 W up to one kW range

The capital cost of a PV power system is considered relatively high, which is why these systems are not yet widely spread. In order to minimize capital costs, it is necessary to match the load characteristics with the PV array characteristic. This can be achieved either by including a maximum power point tracker in the system or by appropriate selection of the motor constants, based on improving the system output performance as maximizing combination of parallel and series cells (Koner, 1995). Sufficient radiation must be available for a PV pumping system to start its pumping operation. This radiation level is called the radiation threshold. Both the existence of a radiation threshold and the nonlinear dependence on radiation level make the analysis of a PV pumping system and prediction of its performance a difficult process.

This investigation was undertaken to study of the performance and economic evaluation of SPV-powered drip irrigation system with regard to different module combinations and water operating heads.

MATERIALS AND METHODS

1. Experimental site

The experiments were carried out in the premises of Rice Mechanization Center at Meet El-Deeba, Kafr El-Sheikh Governorate, which lies at latitude 31.07°N and longitude 30.57°E during clear sunny days in winter 2005/2006. Texture of soil in the experimental site was clay.

2. Installation of solar photovoltaic array and drip irrigation system

A typical scheme of a PV powered drip irrigation system which comprises PV array, battery, submersible pump and drip irrigation system is depicted in Fig. 1.

2.1. PV array assembly

The PV array has a capacity of 140 peak Watt (4 modules, 35 peak Watt each) and mounted on an inclined angle of 30º from the horizontal plane. The PV array has got a tracking arrangement for orienting the panel towards east (from 9.00 to 12.00 hrs), south (from 12.00 to 14.00 hrs) and west (from 14.00 to 5.00 hrs) directions. One black gold lead-acid deep-cycle battery of 0.960 kWh capacity (charged fully before starting the experiments) was used for storage of power generated by the PV array during day time to meet load requirements at no insolation. For the electrical connections of about 4 m distance between the power source and load (submersible pump), the 50 mm^2 cable is used. This wire is sufficient to keep the voltage loss of the PV panel and battery less than 1.0% at the mentioned distance.

2.2. Drip irrigation system

The drip irrigation system consisted of the following components:

Submersible pump of D.C. type, 12 V, 7 Amp, model SBL-2512 B, outlet diameter of 25 mm, delivery volume of 70 l/min, delivery head of 6 m, motor power of 55 W.

The pump was settled in the water sump with mainline of 25 m long and 50 mm diameter. Two sub-mains 25 mm diameter and lateral lines 16 mm diameter and 20 m length with 30 cm spacing between emitters were used. Each lateral line was connected to the sub-main line through a ball valve.

The system was provided with screen filter and control unit (valves) to adjust pressure head and water flow. Six lateral lines with built-in (GR) emitter were used in the present study as shown in Fig. 2. Laterals were of 16 mm inner diameter, 20 m long, 30 cm spacing between emitters.

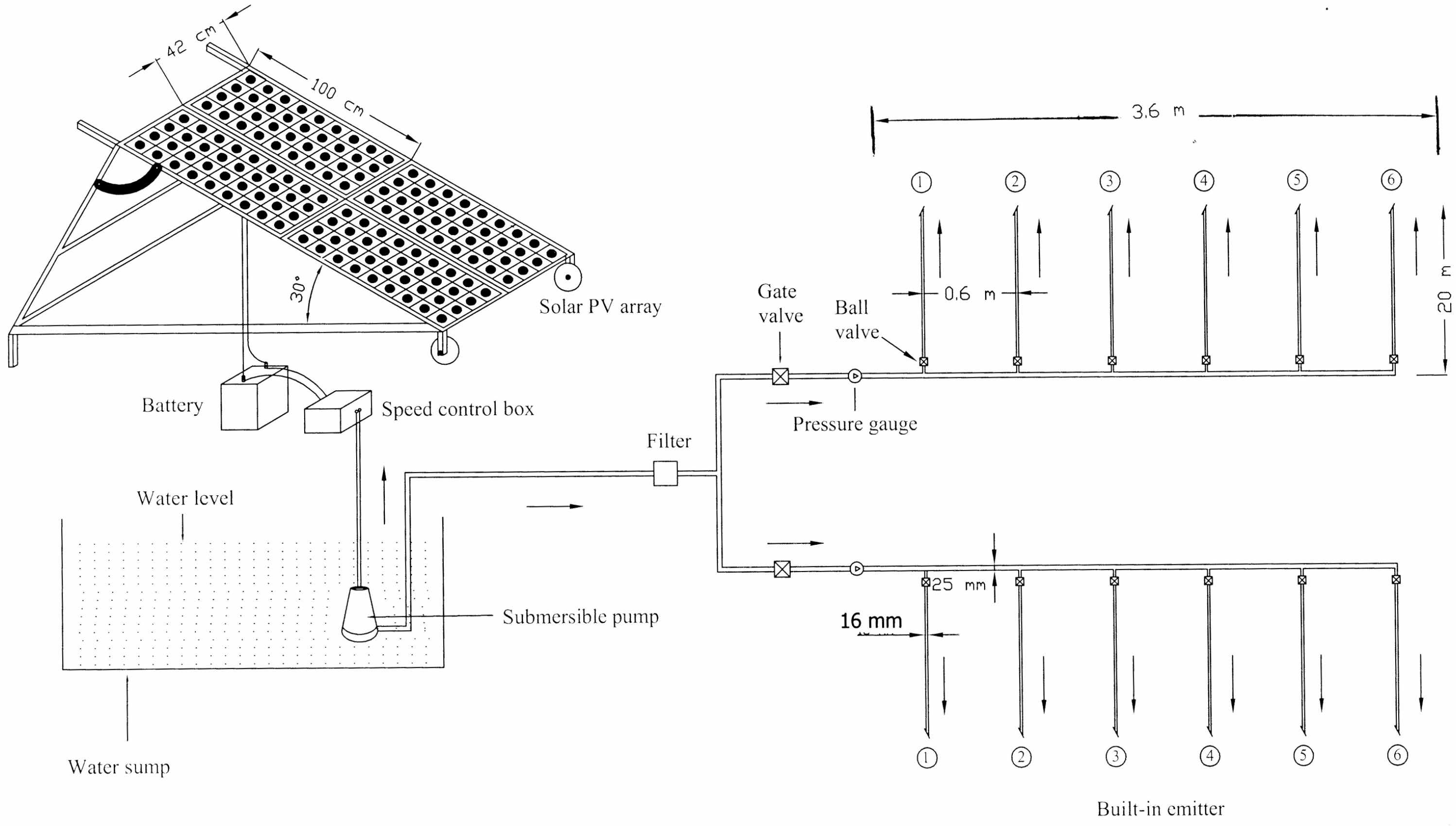

Fig.1: Schematic diagram of solar photovoltaic powered drip irrigation system.

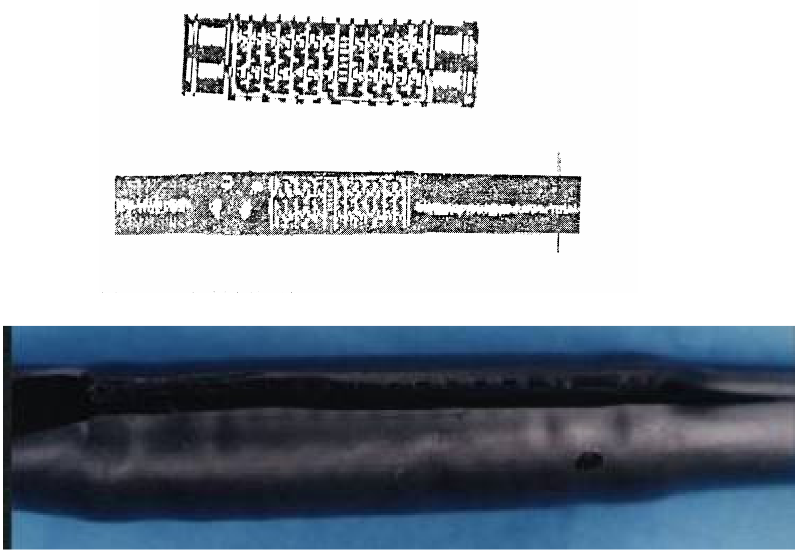

Fig. 2: Sectional view of the built-in (GR) dripper.

3 Test methodology and measurements

Field tests were conducted to characterize the performance of the pump and to measure the daily output of the pump under local climatic and working conditions. This was accomplished by different module combinations. However, it is abase to determine the overall efficiencies of the solar pumping system at various solar radiation levels and the solar radiation required to start the pump in the morning. The data were collected during clear sunny days for short and long-terms tests (10 and 60 min intervals, respectively). The recorded parameters that affect the SPV pump performance were as follows:

Insolation (W/m^2) was measured with a thermoelectric pyranometer in the plane of the PV panel. The DC open circuit voltage, V; load voltage, V; short circuit current, Amp., and load current, Amp., of the panel were measured with the help of multimeter.

The T type copper-constantan thermocouples were used to measure and record the ambient air temperature, T_{amb}, and panel temperature, T_{panel}, by setting one thermocouple at the backside of the panel. Different readings were taken with the help of digital record. Wind velocity (m/s) was measured with help of an anemomaster model 24-6111- made in Japan.

The free pump discharge was measured using volumetric method with a graduated bucket and stop watch, while incase of drip system was fitted; the pump discharge was computed by summing up the discharge of all drippers under different operating heads. The head or water delivery pressure was measured with low range pressure gauge.

4 Energy analysis of the SPV-pumps

In order to study the energy conversion from insolation to water flow the following equations were used:

The insolation to the PV array gives the input power (P_{in}) to the system (Hamza and Taha, 1995):

$$P_{in} = Ins \text{ x } a \quad , W \qquad (1)$$

The DC output power (P_{output}) from the PV array is given by:

$$P_{output} = V_{oc} \times I_{sc} \quad , W \qquad (2)$$

Where: Ins = insolation, W/m^2, a = solar module area, m^2,

V_{oc} = open circuit voltage, V and I_{sc} = short circuit current, A

The hydraulic power output of the pump (P_h) is the power required to lift a volume of water through a given head:

$$P_h = \rho \text{ x } g \text{ x } Q \text{ x } H \quad , W \qquad (3)$$

Where: ρ = water density, kg/m^3, g = acceleration of gravity, m/s^2

Q = water discharge, m^3/s and H = total pumping head, m

PV panel efficiency (η_{panel}) is the measure of how efficient the PV panel is in converting sunlight to electricity:

$$\eta_{panel} = \frac{P_{max}}{P_{in}} = \frac{V_{OC} \times I_{SC} \times FF}{Ins \times a} \times 100 \qquad (4)$$

Where: FF = fill factor which equals about 0.67 for Si.

Subsystem efficiency (η_s) is the efficiency of the entire system components:

$$\eta_s = (P_h / P_{output}) \text{ x}100, \ \% \qquad (5)$$

Overall efficiency ($\eta_{overall}$) indicates how efficiently the overall system converts insolation into water delivery at a given head.

$$\eta_{overall} = (P_h / P_{in}) \text{ x } 100, \ \%$$

or $$\eta_{overall} = \eta_{panel} \text{ x } \eta_s \qquad (6)$$

The following equation was used to calculate variation of the emitter flow rate (Wu, 1992):

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} x\, 100 \qquad (7)$$

Where: q_{max} and q_{min} = maximum and minimum emitter flow rate, l/h, respectively.

The emission uniformity, EU_f, which indicates the uniformity in the discharge from drippers based on field evaluation, is found by using the following relation (Nakayama et al., 1979):

$$EU_f = 100\, q_n / q_a \qquad (8)$$

The variation of coefficient of manufacturing, C_v, is found by using the following relation (Keller and Karmeli,1974):

$$C_v = (S_d / q_a) \text{ x } 100 \qquad (9)$$

Where: q_n = the average of the flow rate of 1/4 drippers discharging of lowest rate, q_a = average of flow rates of all the drippers and

S_d = standard deviation of the emitter's discharge.

5 Cost analysis of the SPV system

The input parameters are the following: equivalent hydraulic energy (in m^4), interest rate, lifetime of PV and drip pumping system components, salvage value, insolation. Equivalent hydraulic energy is defined as the product of pump discharge rate (m^3/day) and total pumping head (m) as follows:

$$E = QH \qquad (10)$$

Where: E = equivalent hydraulic energy, m^4 ; Q = pump outlet flow, m^3 and

H = total pumping head, m.

Equivalent hydraulic energy unit (m^4) is used instead the water volume delivered (m^3) because it encompasses both water volume and pumping head components.

The levelized annual cost of the PV drip irrigation system comprises annual capital recovery cost, and annual costs of operation and maintenance, taxes and insurance, etc. The annual capital recovery cost in turn, can be computed as a product of the capital cost, C_o, and the capital recovery factor (Riggs et al. 1996):

$$Annual\ capital\ re\cos\!v\,ery\ \cos t = C_o\left[\frac{d\,(1+d)^n}{(1+d)^n-1}\right] \qquad (11)$$

And cost annuity per equivalent hydraulic energy unit (C) can be expressed as:

$$C = A/E \qquad (12)$$

Where:

C_o = capital cost,

d = discount rate (assumed to be 10%),

n = expected useful life (20 years for PV array, 3 years for battery and 10 years for pumping irrigation system),

A = annuity cost and E = equivalent hydraulic energy unit

This portable PV pump has the advantage of easy movement from place to place within the field (1152 m^2/day), where different crops are cultivated in different seasons, and hence its annual use can be increased. By applying this system on large scale, the capital cost will be reduced. In this work, a water requirement of 31 and 104 m^4 has been adopted for 2 and 4.5 m pump operating heads, respectively, as an output unit at 4.43 kWh/m^2 insolation. The capital cost of PV-battery stand-alone is about 4450 LE (1 US $ = 5.73 LE) per 0.140 kW_p and 0.960 kWh for PV array and battery, respectively. Meanwhile, the capital costs for the pump and fitted drip systems was about 334.5 LE/144 m^2 (2810 LE/fed).

Data analyses were carried out using MS Excel. Analysis of variance and least significant difference tests were conducted to test significance among variables means.

RESULTS AND DISCUSSION

The main parameters affect the system performance are pump operating head, distribution frequency of insolation and array size.

1 Effect of weather conditions on the panel performance

The average daily insolation, Ins, measured on the module surface for different clear sunny days was 3.95 kWh/m^2/d (average daily of 493.82 W/m^2). This result is corresponding to 16.44°C, 28.78°C and 1.06 m/s for average of ambient temperature, panel temperature and wind velocity, respectively, during winter. The recorded data from the field indicated that higher Ins was observed before noon in comparison to that in the afternoon (Fig. 3). Lower values of insolation, S_{Ins}, at 12.00 and 1400 hrs indicated that the sun rays fall at an angle. However, when the panel faced southward the sun rays were perpendicular to the array, resulting in increased insolation values, which peaked at 13.00 h.

The electrical power outputs (open circuit voltage, V_{oc}, and short circuit current, I_{sc}) of different module combinations (2, 3 and 4 modules) were measured for typical clear sunny days in winter 2005-2006. The power output behaviour with respect to Ins and cell or module temperature were studied. The analysis of recorded data indicated that the power output of solar module changed highly significantly with Ins during winter season which may be due to increase of clearness index.

Figure 3 shows the variation of power output, P_{output}, of solar module, load power and conversion efficiency as affected by Ins , panel temperature, T_p and WV with respect to zonal time of the day. The maximum P_{output} were recorded at 13.00 h during tested days. The reason for that may be due to, the generated short circuit current, I_{sc}, which increased more than the drop in voltage at noon. The average drops in voltage were 1.91, 2.87 and 2.95%, while the average generated short circuit current increased by 15.34, 14.57 and 13.04% for modules 2, 3 and 4 respectively. The average daily P_{output} of 65.46, 96.69 and 124.55 W with standard deviation of 7.57, 10.62 and 14.58

were recorded for modules 2, 3 and 4, respectively. The average daily load power (solar PV pump) were 33.49 64.65 and 79.09 W. Also, the higher P_{output} at mornings was observed in comparison to those in the evenings, this may be due to the module heating up in the after noon more than mornings.

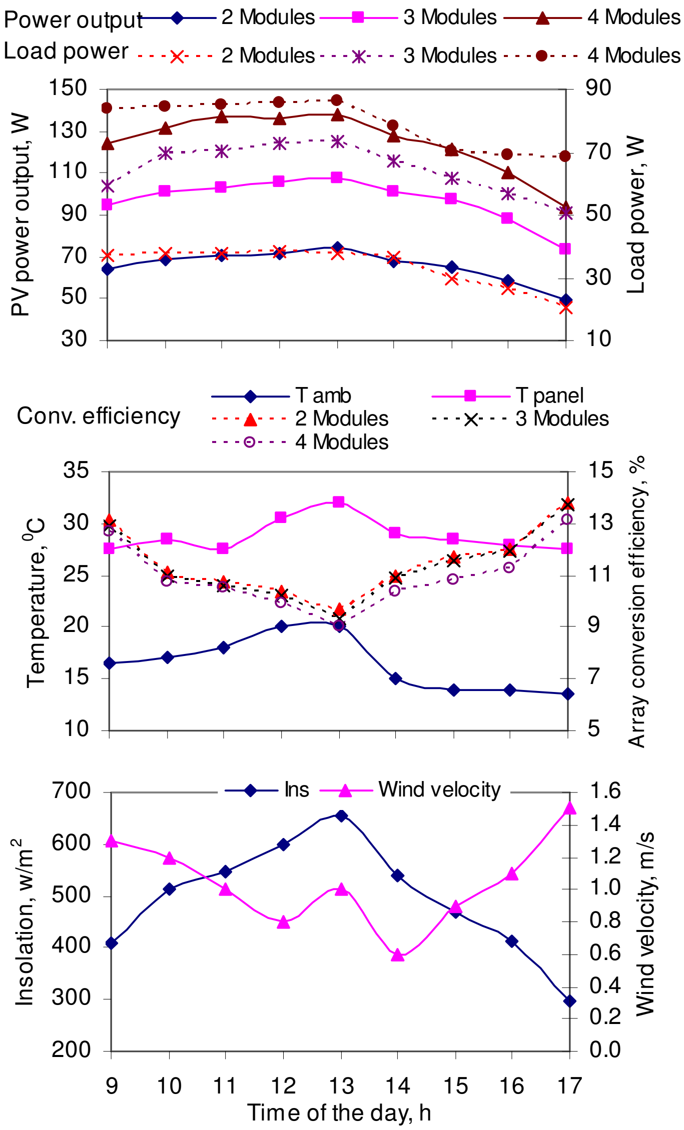

Fig. 3: SPV power performance without and with load (connected to the pump) with respect to average ambient micro-climate conditions for clear sunny days during winter 2005-2006.

In addition to, the higher Ins at mornings in comparison to those in the after noon. It was found that increasing modules combinations from 2 to 3 and 4 modules caused an increase of P_{output} by 32.3 and 47.44%, respectively.

The maximum open circuit voltages were observed on the mornings when the module temperature was lower; this is in agreement with that observed by Onyegegbu (1989). On clear days, the short circuit current is linearly proportional to Ins, where it increases with increasing insolation.

It is clear that increasing Ins and T_{amb} caused a rise in the module temperature. The higher cell/module temperature, T_p, causes a reduction of peak power. This increase in cell temperature at noon would arise due to high insolation heating, low wind velocity with the consequent low heat transfer from the cell to the ambient, and a high ambient temperature. The average daily T_p of 28.78 °C corresponding to average daily T_{amb} of 16.44 °C and average daily Ins of 493.82 W/m^2 was recorded for clear sunny days.

2 PV conversion efficiency

The hourly variation of conversion efficiency, η_{panel}, is illustrated in Fig. 3. it is clear that, the η_{panel} is relatively higher during the early and late hours of the day as compared to midday as a result of thermal effects of insolation, i.e. η_{panel} is inversely proportional to the module temperature

The average daily η_{panel} of 11.38, 11.22 and 10.83% corresponding to average T_p of 28.78 ºC were recorded during winter for modules 2, 3 and 4, respectively. Meanwhile, the average daily η_{panel} of 8.76% corresponding to average T_p of 47.55 ºC was recorded for 4 modules during summer (Eltawil and Imara, 2005). It was found that, the efficiency drops during the summer season as compared to winter. Also, the results showed that the conversion efficiency decreased with the increase of module combinations. The reason for that may be attributed to the fact that increasing module combinations cause an increase in the generated currents, which led to heating up of wires and hence increased losses.

3 Variations in pump discharge with insolation

The discharge of pump under no load (free discharge) and fitted drip system was evaluated. The recorded data revealed that the discharge was directly proportional to insolation. It was found that the highest free discharges of 36.15, 49.5 and 56 l/min at static head of 2.5 m corresponding to insolation of 655.45 W/m^2 were recorded at 13.0 h for modules 2, 3 and 4, respectively. Meanwhile, in another test, the maximum discharges were 44.5, 55 and 63.5 l/min corresponding to insolation of 905.3 W/m^2 for solar modules 2, 3 and 4, respectively. The drops in insolation falling on the panel surface at 12.00 and 14.00 h showed that to get more output from PV pump the panel needs to be kept towards east up to 11.30 h and then it should be oriented towards south till 13.30 h and subsequently tracked towards west.

Another test was carried out with and without load, and the free discharge of the pump was found to be greater than the fitted drip pump discharge. The gape between the two discharges was found to be small at the lower insolation values but increases with the increase of the insolation values, as shown in Fig. 4. It may be noted that the free pump discharge keeps increasing with increasing solar insolation but the fitted drip discharge stayed almost constant (slightly increased) beyond insolation of 650.6 W/m^2. This may be attributed to that at this level of insolation; the drippers reached their rated discharge.

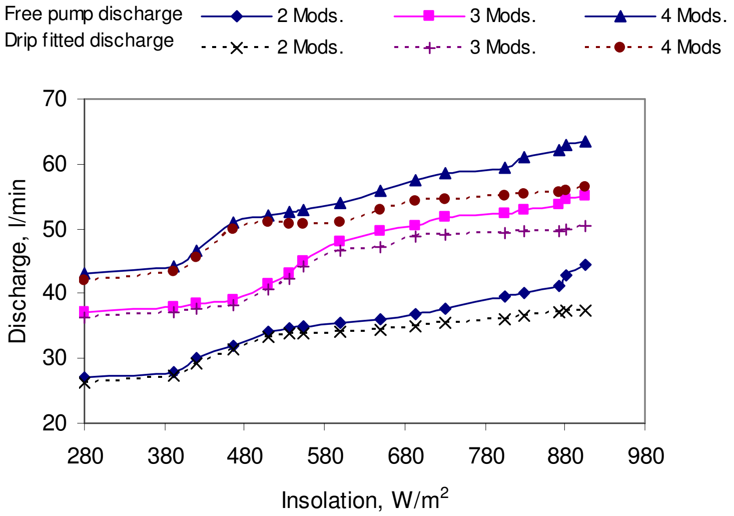

Fig. 4: Variation of pump discharge at load and no-load conditions with different solar PV modules for selected insolation.

The gap between the two graphs (with & without load) shows the rate of discharge lost by the coupling drip system. The variation in pump discharge was more in the case of no load conditions. The average free discharges were 35.92, 46.87 and 54.83 l/min corresponding to average insolation of 632.94 W/m^2 for modules 2, 3 and 4, respectively. Meanwhile under load (drip system fitted) there was a reduction in the discharge. The reductions in the discharges were 4.42, 6.32 and 6.05% for modules 2, 3 and 4, respectively. It is clear that the discharge increases with the decrease in head. As the pumping head decreases from 4.5 to 2.0 m, the average free discharge of water increases from 26.1 to 35.92; 39.8 to 48.87 and 48.7 to 57.75 l/min for 2, 3 and 4 solar modules, respectively as shown in Fig. 5.

When the drip system was fitted, the average discharge of water increased from 23.0 to 35.3; 37.0 to 48.1 and 44.5 to 57.2 l/min, while the pumping head decreased from 4.5 to 2.0 m for 2, 3 and 4 solar modules, respectively. These values corresponding to insolation ranged from 208 to 905.3 W/m^2. Larger discharge is needed when it is required to pump for drinking water supply. However, to run a drip system, there is a need to have a minimum pressure at the delivery side. This indicates that the dripper should be compatible to these pressure values. Since the reduction in operating pressure allows more water to be pumped with the available limited energy supply, suitable low-pressure compensating drippers are preferable to irrigate larger area (Norum and Zoldoske, 1985 and as in Awady et al., 2002).

4 Solar pump performance characteristics

Performance of solar pump under two load conditions (free and fitted drip system) was studied through the standard characteristic curves, drawn in Fig. 5. It is clear that increasing the pumping head caused an increase in the hydraulic power and a decrease in the discharge with and without fitted drip system. The minimum and maximum hydraulic powers of 11.54 and 35.83 % were recorded with 2 and 4 modules, respectively. There was a small reduction of hydraulic power when the drip system was fitted. Increasing of pumping head from 2 to 4.5 m causes an increase in the hydraulic power by 46.62, 73.04 and 75.08% for modules 2, 3 and 4 in case of fitted drip system, while it was increased by 63.4, 83.23 and 89.78%, respectively in case of free discharge.

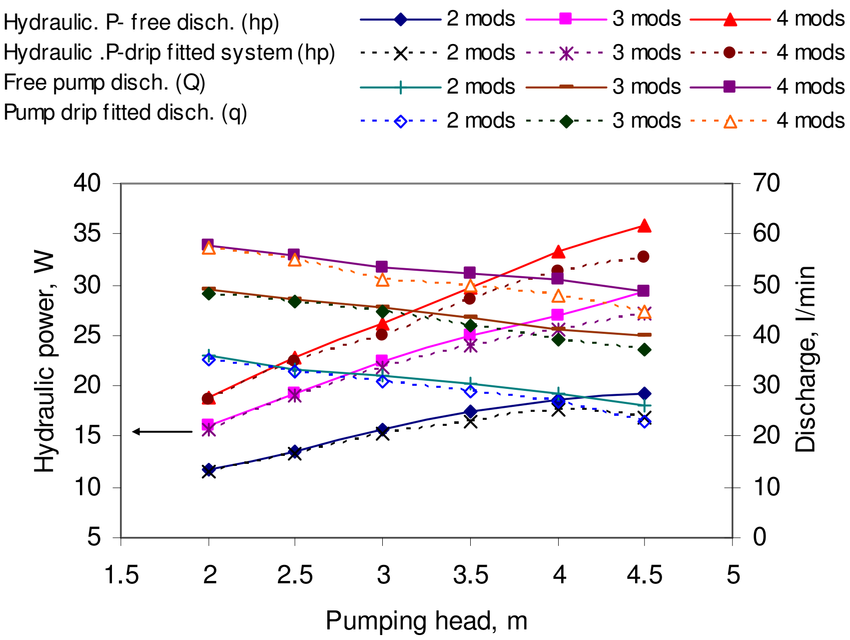

Fig. 5: Performance characteristics curve of pump under free and fitted drip discharges.

An important aspect that must be considered in the search for an optimum system design is the sensitivity of the system efficiency to the change in water head. It was found that at low insolation, where input power to the subsystem is low, subsystem efficiency is too low for all pumping head profiles. However, higher pumping head profiles showed lower subsystem efficiency. As insolation increases, input power to the subsystem increases thereby components starts to work near or at its rated conditions resulting eventually in higher efficiencies. As the rated pump speed is reached, insolation is no longer a dominant influence and pumping head becomes the dominant factor affecting subsystem efficiency.

As shown in Fig. 6, the subsystem efficiency, η_s, approaches its maximum value corresponding to a total head of approximately 4.5 m. For higher heads, the η_s decreases significantly due to the increase of the power threshold of the system, also by increasing the number of module combinations. Therefore, the higher and lower subsystem efficiencies were recorded with 2 and 4 modules, respectively, in case of both free and fitted drip systems. Increasing pumping head from 2 to 4 m causes an increase ranging from ١٧,٨٧ to 40.20; 15.97 to 35.92 and 13.93 to 31.34 corresponding to modules 2, 3 and 4, respectively in case of free discharge. In case of fitted drip system, the subsystem efficiencies increased from 16.73 to 37.66; 15.26 to 34.34 and 13.08 to 29.44 for modules 2, 3 and 4, respectively.

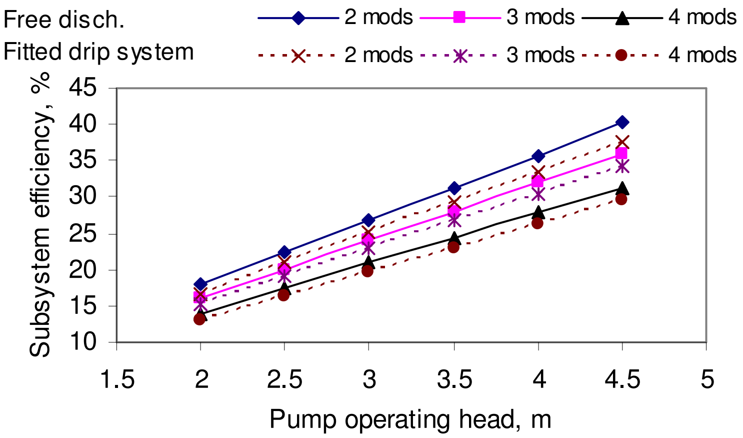

Fig. 6: PV pumping subsystem efficiency versus insolation and PV array sizes.

Figure 7 shows the overall efficiency of PV pumping system versus delivery head, discharge and PV array sizes. It was found that the overall efficiency, $\eta_{overall}$, followed the same trend of subsystem efficiency. The average maximum $\eta_{overall}$ was 5.22 at pumping head of 4.5 m for 2 modules combinations, while the minimum $\eta_{overall}$ was 1.77% at 2 m head incase of 4 modules.

5 Dripper performance

Figure 8 shows the emission uniformity and variation of coefficient of manufacturing under field conditions for built-in (GR) dripper. The emission uniformity was found to be 92.2-94.0%. Meanwhile, the variation of coefficient of manufacturing was 5.6-3.4%. Since the built-in dripper has low value of variation in coefficient of manufacturing and high emission uniformity, therefore using this type of dripper can maximize the benefit of SPV powered drip irrigation system.

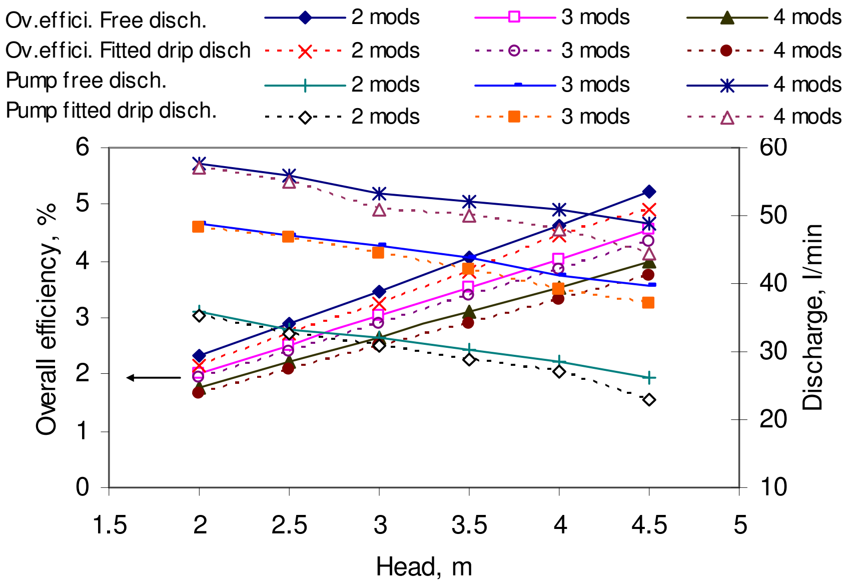

Fig. 7: Overall efficiency of PV pumping system versus delivery head, discharge and PV array sizes.

6 Cost analysis

The estimated annual cost revealed that the higher percentage annual costs of 66 and 13.6% are related to the modules and the battery, respectively. While it represents a 5.15% of total cost for pump and drip system. The annual cost estimation indicated that the unit cost of PV electricity was 0.284 and 0.422 LE /kWh for modules 2 and 4, respectively, at the module price of 2 US $ per W_p without governmental subsidies. It may be noted that increasing PV installed capacity will reduce the unit cost of electricity, but the optimum size should be adopted to justify the investment. It is observed that the annual cost (life cycle cost) of PV system is highly sensitive to the module price. The cost of the water unit pumped by PV systems is much less than that pumped using diesel systems at low discharges (Mahmoud and El Nather, 2003).

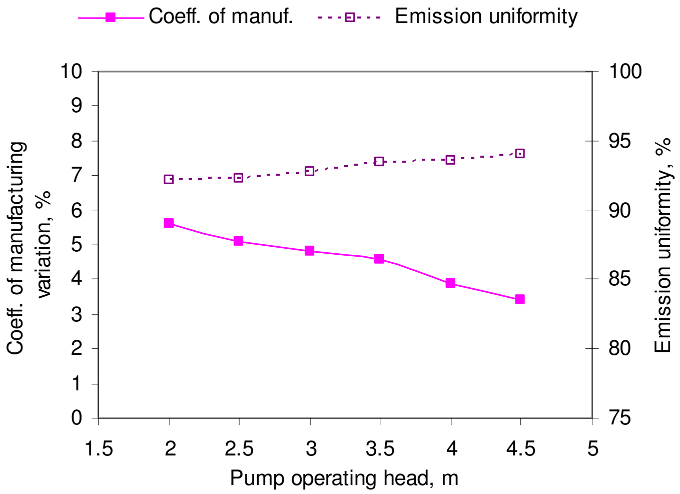

Fig. 8: Variation of coefficient of manufacturing and emission uniformity with pumping head.

The cost annuity per equivalent hydraulic energy unit were 23.26 and 6.93 LE/104 m^4 for fitted built-in drip system at 2 and 4.5 m operating head, respectively. This means that increasing the pump operating head led to decrease in cost annuity per equivalent hydraulic energy unit, so it is recommended to use the higher pumping head within the optimal range of the pump. Because of its high capital cost, PV water pumping applications were limited in the past to small-scale applications. Currently, the use of medium scale systems up to 11 kWp is not only becoming feasible but also can be introduced as investment portable projects (Maycock, 1999). The cost of PV is likely to be brought down from the present value by the near future. With low cost solar cells, the PV operated drip system for growing different crops would be a boon for the farmers. At this stage it is recommended that the system should be extensively tested in the fields to get a feed back from the farmers.

CONCLUSION

From the above results the following conclusions are derived:

- The average energy output of ٠,٥٢٤, 0.774 and ٠,٩٩٦ kWh/d and average load energy of 0.268, 0.517 and 0.624 kWh/d were recorded for modules 2, 3 and 4, respectively.

- The average daily η_{panel} of 11.38, 11.22 and 10.83% corresponding to average panel temperature of 28.78 ºC were recorded during winter for modules 2, 3 and 4, respectively.
- The maximum pump discharges were 44.5, 55 and 63.5 l/min corresponding to insolation of 905.3 W/m^2 for solar modules 2, 3 and 4, respectively.
- An optimum system parameter search can greatly enhance the performance of a PV pumping system to achieve the required water demand for living in a remote area.
- Increasing of pumping head from 2 to 4.5 m causes an increase in the hydraulic power by 46.62, 73.04 and 75.08% for modules 2, 3 and 4 in case of fitted drip system.
- The water head plays an important role in evaluating the economic feasibility of photovoltaic powered water pumping systems.
- The emission uniformity of built-in (GR) dripper ranged from 92.2 to 94.0%.
- The cost annuity per equivalent hydraulic energy unit was 23.26 and 6.93 LE/104 m4 for fitted built-in drip system at 2 and 4.5 m operating head, respectively.
- A well-designed directly coupled PV pumping systems is feasible in the Egyptian climate even at the current expensive prices of PV modules.
- Costs of PV equipment and water pumps are expected to decrease more and more over the next few years as the demand for PV systems goes up worldwide. These factors will make PV pumping systems more economic in the near future.
- The results of the present work should encourage for wide installation of solar energy systems and provide the farmers with subsidies to keep our environment healthy and clean.

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الملخص العربي

أداء نظام ري بالتنقيط مصغر يعمل بالخلايا الكهروضوئية صالح للمناطق النائية

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تهدف هذه الدراسة إلى تقييم أداء الخلايا الكهروضوئية لشغيل نظام ري بالتنقيط مصغر صالح للمناطق النائية و البعيدة عن شبكة الكهرباء. تم دراسة أداء الخلايا الكهروضوئية تحت ظروف التجربة كما تم دراسة أداء المضخة بدون تحميل (تصرف حر) وتحت تحميل (تشغيل نظام الري بالتنقبط) وذلك عند ضغوط تشغيل مختلفة (٢، ٢,٥، ٣، ٣,٥، ٤ و٤,٥ م) وعدد من موديول الخلايا الكهروضوئية (٢، ٣ و ٤ موديول) ، كما تم تقدير التكاليف للطاقة الهيدروليكية المكافئة ($م^{٤}$ بمعنى معدل تصرف المضخة x الضاغط الكلى للماء).

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و قد أوضحت النتائج ما يلي:-

- كان متوسط الطاقة المنتجة بواسطة الخلايا هو ٠,٥٢٤ ، ٠,٧٧٤ و ٠,٩٩٦ ك. وات. س/يوم بينما كان متوسط الطاقة المطلوبة لتشغيل الحمل هو ٠,٢٦٨ ، ٠,٥١٧ ، ٠,٦٢٤ ك. وات. س/يوم وذلك عند استخدام ٢ ، ٣ و ٤ موديول ، على الترتيب.

- كان المتوسط اليومي لكفاءة الخلايا الكهروضوئية هو ١١,٣٨ ، ١١,٢٢ و ١٠,٨٣ ٪ عند متوسط درجة حرارة للخلايا مقدارة ٢٨,٧٨ °م وذلك عند استخدام ٢ ، ٣ و ٤ موديول ، على الترتيب.

- كَانتْ أقصى تصرفات للمضخّة هى ٤٤,٥، ٥٥ و ٦٣,٥ لتر/د عند اشعاع شمسى مقداره ٩٠٥,٣ وات/م^{٢} وذلك عند استخدام ٢ ، ٣ و ٤ موديول ، على الترتيب.

- وجد أن زيادة ضاغط الماء مِنْ ٢ إلى ٤,٥ م قد أحدث زيادةً في القدرة الهيدروليكية بحوالي ٤٦,٦٢، ٧٣,٠٤ و٧٥,٠٨ % وذلك عند استخدام ٢ ، ٣ و ٤ موديول ، على الترتيب.

- يَلْعبُ ضاغط الماء دوراً مهماً في تَقييم العمليةِ الإقتصاديةِ لَضْخُّ المياه باستخدام الخلايا الكهروضوئية.

- انتظامية التصرف للنقاط built-in (GR) كانت حوالى ٩٢,٢-٩٤,٠.

- التكلفة السنوية لكلّ وحدةِ طاقةِ هيدروليكيةِ مكافئةِ كَانتْ حوالي ٦,٩٣ جنيه/١٠^{٤} م^{٤} عند استخدام ضاغط ماء مقداره ٤,٥ م.

- يوصى باستخدام النقاط من النوع built-in حيث أن لَهُ قِيَم منخفضة لمعامل الإختلاف فى التصنيع ، تكلفة منخفضة و انتظامية جيدة فى التصرف.

- وجد أن استخدام متغيرات النظامِ المثلى يُمْكِنُ أَنْ تُحسّن َكثيراً من أداءَ نظام ضخّ المياه لإنْجاز الاحتياجات المائية اللازمة للمعيشة في المناطق البعيدة.

- من مزايا النظام الشمسى أنه يعطي أقصى طاقة عند الظهيرة عندما يكون الاستهلاك عند حده الأقصى. حيث أن الطلب على نظام الخلايا الكهروضوئية ازداد حول العالم فإن ذلك سيَجْعلُ أنظمة الضخّ بالخلايا الفوتوفولطية أكثر إقتصادا في المستقبل القريبِ.

- وعلى ذلك فإن الرى بالتنقيط يكون مناسب للاستخدام مع الطاقة الشمسية، حيث يتطلب ذلك تقليل معدل التصرف كما أنه يناسب المناطق النائية و البعيدة لندرة الوقود والأيدي العاملة.