Efficiency Improvement of a Dual PV Water Pumping System on a Desert Well by Solar Matched Load Control

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***Abstract*- Two similar PV powered water pumping systems (PVPS) with a programmable control system, which enables matching between the loads (pumps) and the generated PV power according to solar radiation intensity, are treated in this paper. Testing results show an annual gain of 7.4% in water pumped through using the control system. Moreover, up to 16% increment in daily water pumped, especially in winter days of moderate solar radiation (≈2.8 kWh/m^2.day), has been measured. This means that a considerable reduction of the water cost is achieved and thereby the feasibility of PVPS is increased. Further increments of total system efficiency achieved by utilizing PV modules of higher efficiency and by mounting the PV array on a support structure with adjustable tilt angle are discussed. Decreasing the hydraulic output of the pumping system, due to the increase of temperature in summer, is demonstrated through field testing results.**

Keywords- Photovoltaic Powered Water Pumping Systems; Solar Electric Power Converters; Water Supply in Rural Areas

I. INTRODUCTION

Water pumping from wells located in rural areas without electric grids has occurred before the middle of the 1970’s mainly by diesel motors where the fuel cost was very low (10 US$/Barrel). The cost of fuel has continuously increased and now exceeds 100 US$/Barrel.

Utilization of PV in providing power to water pumping systems began in the late 1970's and rapidly spread during the following years, especially to rural areas of high solar energy potential. This PV application is considered very successful since the higher water consumption occurs in summer during the period of maximum solar energy, when the PV pumping system (PVPS) delivers more water. For this application, new different electronic inverter types have been developed to enable the utilization of ordinary three phase asynchronous motor pumps and to make the PVPSs more applicable and reliable.

The cost of PV generators has slowly decreased during the last thirty from 12 US$ to 2 US$/Peak Watt. Feasibility studies on utilizing PVPS and diesel motors carried out in Jordan in 1988, where the diesel fuel cost was only 1/10 of its current price and the PV cost was 3 times of its current price, had shown that PVPS is more feasible for a wide load range than diesel motors [1]. This means a similar economic study now respecting the current prices of PV and diesel fuel would be surely in favor of utilizing PVPS [2]. The costs of diesel fuel and the associated maintenance are always increasing. In addition, contrary to PV systems, diesel motors encounter frequent maintenance problems and have negative impacts on the environment.

PV water pumping systems on rural wells are usually designed to deliver a definite daily volume at a certain discharge head but mostly they include no load control [2]. This paper presents the design of two similar PVPSs with a programmable control system that can switch the appropriate system components according to the solar radiation level to increase the system efficiency. The two PVPSs were tested with and without control system for two years. The obtained testing results are illustrated and discussed in this paper. The cost of the locally built control system amount to 300 US$ which represents a very small percentage of the total cost of the PVPS.

II. WELL SITE, CLIMATE AND WATER DEMANDS

A. Location and Target Groups

The water well in this study is located in the eastern part of Jordan with the coordinates: 31°47' north of Equator and 36°39' east of Greenwich in a thinly populated desert area. The inhabitants are nomadic Bedouins who live in tents and depend mainly on the breeding of sheep, goats and camels. The water authority of Jordan provides these Bedouins and their livestock with water from such desert wells at no cost.

B. Climate and Solar Energy

The well site has a desert climate, which is extremely hot in summer and cold in winter. Maximum temperatures of 42 Cº during the main summer months are usually recorded while minimum temperatures of 3Cº during winter months are possible. The site has a high solar energy potential with an annual average solar radiation intensity on horizontal surface amounting to E_{sd}= 5.3 kWh/m^2.day. The average of solar radiation intensity during the main winter months (December-March) is about 3.2 kWh/m^2.day while it exceeds 5.7 kWh/m^2.day in the remaining eight months. The total sunshine duration per year amounts to about 3000 hours [3].

C. Desert Well Characteristics and Water Demands

The water well is artesian with the specifications: total depth = 130 m, casing diameter = l2 inch, water static level = 0.95 m, water dynamic level = 11.4 m, yield = 75 m^3/h and salinity = 1326 ppm. The daily average of water required on the well site is 120 m^3.

III. PHOTOVOLTAIC WATER PUMPING SYSTEM (PVPS)

In general there are two types of PVPS represented in DC and AC systems. A DC system, containing a DC motor with brushes coupled to a pump, is usually supplied directly by DC power produced from the PV generator. These systems are mostly small and suffer frequent maintenance problems. Therefore, they are rarely used in large power ranges.

AC systems have mostly three-phase asynchronous motor pumps, which require inverters to convert the DC power produced by the PV generator to AC power of three phase voltages and currents [4]. This paper only deals with AC systems.

A. System Design

All PVPSs (AC systems) are similar in design and consist mainly of a PV generator, inverter with three-phase output voltage (50 Hz) and an asynchronous motor pump. Fig. 1 illustrates the schematic diagram for two such systems (PV1, INV1, ASM1, PMP1 and PV2, INV2, ASM2, PMP2) with a programmable control system. Usually, only one system is built on one well without control system. The two systems with the control system (Fig. 1) were built on the desert well for research activities as well as providing water to the desert inhabitants and their cattle.

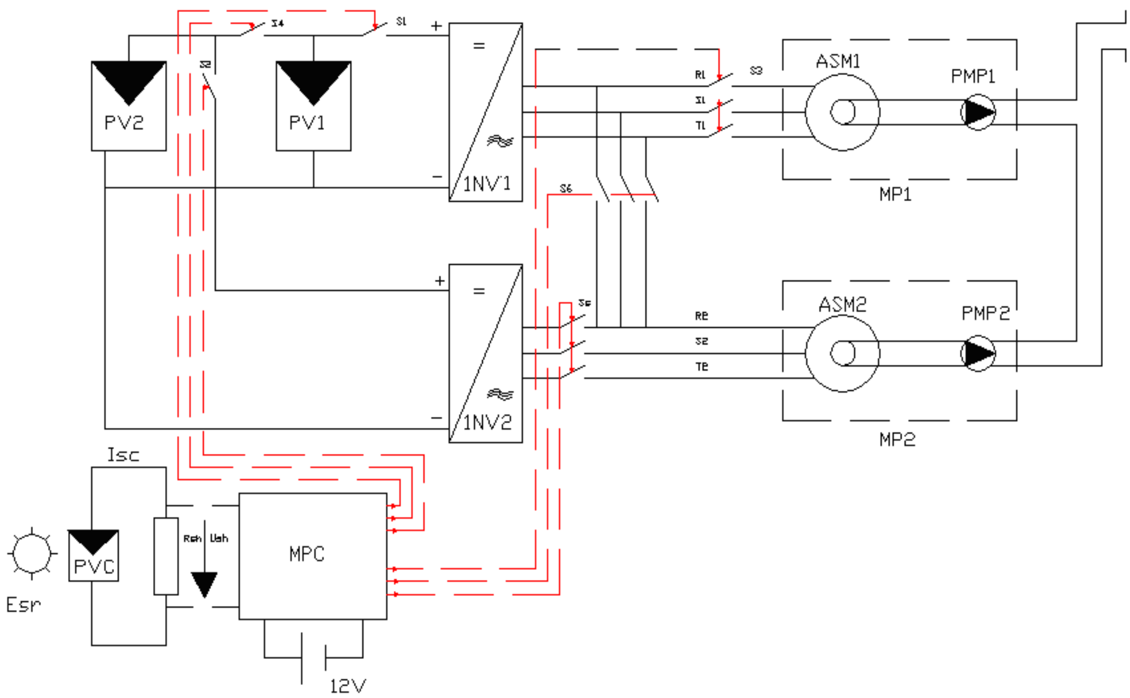

Fig. 1 Dual photovoltaic water pumping system with solar matched load control

B. Control System

The control system (MPC) in Fig. 1 was developed locally to switch the appropriate load (1 or 2 pumps) according to the output power of the PV generator, which is directly proportional to the solar radiation intensity, to one or two PV arrays (PVI, PV2) [5]. Electrical connections between the system components occur through the controllable switches S1-S6 (Fig. 1).

The control system, which includes a microprocessor and memory, is programmable according to the solar radiation level. With respect to its truth table (Table 1), four connection scenarios are possible.

TABLE 1 TRUTH TABLE OF THE CONTROL SYSTEM (1 = CLOSE, 0 = OPEN)

Switch / No connection	S1	S2	S3	S4	S5	S6	Connected components
C1	1	1	1	0	1	0	(PV1,INV1,MP1)&(PV2,INV2,MP2)
C2	1	0	1	1	0	0	(PV1+PV2), INV1, MP1
C3	1	0	0	1	0	1	(PV1+PV2), INV1, MP2
C4	1	0	1	1	0	1	(PV1+PV2), INV1, (MP1+M P2)

The connection C1 facilitates the operation of each system separately. Cl is appropriate for cloudless periods of high solar radiation (>700 W/m^2). Connection C4 allows the switching of both pumps in parallel to one inverter (INV1) supplied from the parallel-connected PV arrays (PV1+PV2). This connection is appropriate for driving two pumps of different rated powers during periods of moderate solar radiation (400< G <700 W/m^2). Connection C2 and C3 are especially useful since they enable the PVPS to work more efficiently during cloudy periods of low solar radiation levels (<400 W/m^2). C2 and C3 extend the daily pumping time by enabling the PVPS to start pumping earlier and to remain pumping later [5]. In addition, they facilitate the operation of the pumps for longer time at rated power. They also enable the two pumps to be driven alternately, which elongates their lifetime. These advantages result in raising the daily efficiency of the PVPS, as will be illustrated in the testing results (Section VI. B.).

C. System Sizing

In order to compute the daily energy produced by the PV generator and its peak power, the daily-consumed electrical energy by the motor pump has to be identified at the beginning of sizing the PVPS [1]. The hydraulic energy (E_h) required for elevating a water volume (V) to a height (h) is given by the following relation:

$$E_h = \rho V g h \tag{1}$$

Where ρ is the standard water density (1000 kg/m^3) and g is the gravitational acceleration (9.8l m /s^2). Substituting these numbers in Eq. 1 and converting the time in hours, we obtain E_h in kWh as follows:

$$E_h = 0.002725 \cdot V \cdot h \tag{2}$$

Replacing V in Eq. 1 with the flow rate Q (in m^3/h); we obtain the corresponding hydraulic output power of the pump (P_h) in W:

$$P_h = 2.725 Q \cdot h \tag{3}$$

The required daily energy from the PV generator (E_{PV}) in kWh is obtained as follows [1, 6]:

$$E_{PV} = \frac{E_h}{\eta_{inv} . \eta_{mp}} \tag{4}$$

Where η_{inv} and η_{mp} are the efficiency of the inverter and the motor pump, respectively. For standard conditions (STC) where Go=l000 W/m^2, PV cell temperature=25C° and airmas = 1.5, the peak power of the PV generator in kW (P_{pv}) is determined as follows:

$$P_{pv} = \frac{E_{pv} \cdot G_o \cdot S}{E_{sd}} = \frac{2.725 Vh \cdot S}{E_{sd} \eta_{inv} \eta_{mp}} \tag{5}$$

Where E_{sd} is the daily average of solar radiation intensity on the PV surface and S is a safety factor for compensation of sunless periods, resistive losses and temperature effect.

The overall system efficiency (η_{sys}) is obtained as follows:

$$\eta_{sys} = \frac{P_h}{P_{in}} = \frac{2.725 \cdot Q \cdot h}{G \cdot A_{pv}} \tag{6}$$

Where G is the solar radiation intensity on the PV surface and A_{PV} is the total area of PV array constituting the generator.

D. System Specifications

1). PV Array:

Considering the total pumping head (including water table depth, friction losses in the pipes and storage tank height) which is 16 m, a solar radiation of 5 kWh/m^2.day(less than the daily average on the well site amounting to 5.3 kWh/m^2.day for safety) and the daily water demands (V=120 m^3) as well as assuming realistic values for the efficiencies of the inverter and motor pump amounting to η_{inv}=0.97 and η_{mp}=0.4 respectively with a safety factor of S=l.33, then substituting these values in Eq. 5, we obtain the necessary peak power of the PV generator:

$$P_{PV} = 4.22kW$$

Respecting the design of the PVPS illustrated in Fig. 1, this peak power will be equally divided so that each system consists of 2110 peak watt. To build a PV array capable of producing this peak power, a polycrystalline silicon PV module type AEG PQ 10/40/01-Germany of a gross area of 0.494 m^2, a peak power of 38.4 W, an open circuit voltage and short-circuit current of 22.4 V and 2.5 A respectively were selected. This means that 55 modules were necessary to produce the mentioned peak power. In fact, 56 modules were procured to meet the inverter input voltage requirements represented in building of 4 parallel strings each consisting of 14 PV modules connected in series.

The two PV arrays were mounted on a support structure facing south with a constant tilt angle of β=45. The maximum hourly average of solar radiation intensity on the PV surface was measured during March and amounted to G =874 W/m^2. Higher values for G and thereby for E_{sd}, V and η_{sys} could be achieved if a support structure with adjustable tilt angle of the values: β1=latitude, β2=latitude-10 and β3=latitude+20 had been used [6]. Thereby, the solar incidence angle (i) will be adjusted with respect to the variation of solar altitude angle (α), to be smaller, which increases G on the PV surface. For a south facing tilted PV surface, the variation of i and α is given through the following solar geometry equations [6]:

$$\sin\alpha = \sin L \cdot \sin\delta_S + \cos L \cdot \cos\delta_S \cdot \cos H_S \quad (7)$$

$$\cos i = \sin\delta_s \cdot \sin(L-\beta) + \cos\delta_s \cdot \cos(L-\beta) \cdot \cos H_s \quad (8)$$

Where, L is the site latitude, δ_s is the solar declination angle and H_S is the solar hour angle.

2). Inverter:

With respect to Fig. 1, two similar inverters were necessary. The selected inverter type was AEG-Solarverter 3-Germany with an operating input voltage: 135-300 V DC, maximum input current: 16 A , nominal output voltage:127 V AC (3 phase), nominal output current: 14 A AC per phase, short-circuit current: 21 A per phase, output frequency: 50 Hz and nominal output power: 3 kVA.

3). Motor Pump:

The submersible motor pump consists of a three-phase asynchronous motor with an input voltage of 127 V AC and an output power of 2.2 kW coupled to a centrifugal pump of 4 stages (type: Pleuger NE 62-4-Germany) that is rated at 8 m^3/h at 20 m pumping head.

IV. TESTING RESULTS, ANALYSIS AND CONCLUSIONS

The two PVPSs illustrated in Fig. 1 have been continuously measured for four years. An automatic data acquisition system was employed to measure instantaneously the solar radiation intensity on the PV surface, the input/output voltages and currents of the system as well as the discharge of both pumps. The measuring system is programmable and capable of integrating the measured variables, on hourly and daily basis, and is supported with mechanical water flow meters.

A. Results of the Uncontrolled PV Pumping System

The two similar PVPSs illustrated in Fig. 1 were separately exposed to continuous testing during the first two yeas of operation. The main testing results are summarized as follows:

(a) The performances of both systems are very close since they consist of similar components. On an annual basis, the daily average of water volume pumped by system 1 is 67.9 m^3 while the respective volume of system 2 is 66.3 m^3. The small difference is explained by piping length of system 2 which exceeds that of system 1 by 6 m and it includes one elbow 3 inch more and pump 2 is hanging in the well at 6 m deeper than pump l.

(b) On an annual basis, the total daily average of both systems amounts to 134.2 m^3. This volume exceeds the volume of 120 m^3/day, considered in the design, because the daily average of solar radiation intensity during the first testing year was measured to 5.053 kWh/m^2 which exceeds the average considered in the design. In addition, it seems that the safety factor was a little bit higher than it is estimated and we were obliged to increase the computed peak power (Eq. 5) by 38.4 W (1PV modules) in order to meet the voltage level appropriate to the input of the inverter.

(c) The minimum yield for one PVPS was measured to l.l8 m^3/day in January at E_{sd}=670.1 Wh/m^2.day. The daily average for January was measured to V=41.81 m^3/day (at a daily average of E_{sd}=4.25 kWh/m^2.day) which also represents the minimum yield in the year. The maximum pumping yield for one system was measured to V=99.99 m^3/day in March at E_{sd}=6.12 kWh/m^2.day. Fig. 2 illustrates the performance of system 1 and the solar radiation during this day. The daily average for March was measured to 79.96 m^3/day, which represents the maximum yield in the year. The dual system fell short of the design value (V=120 m^3/day) only during the months Dec., Jan. and Feb., where it delivered 112.83, 84.56 and 109.63 m^3/day respectively. Usually, during these winter months, the water demands are less than those in the remaining months.

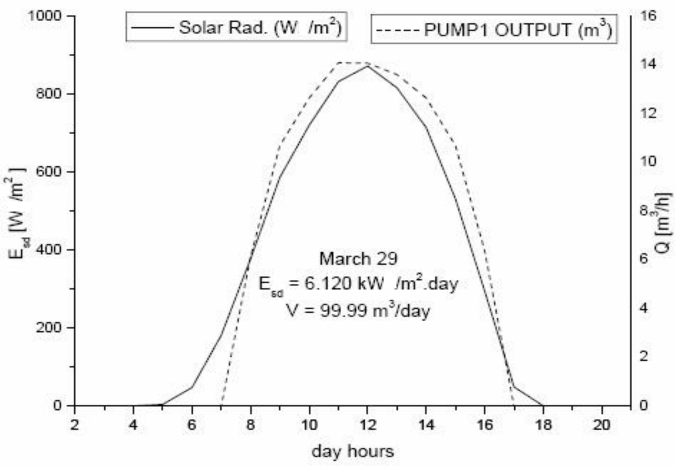

Fig. 2 The water discharge of system 1 and the solar radiation intensity in function of the day hours

(d) The measured annual average efficiencies of the system component are as follows:

$$\eta_{pv} = 7.01\%,\ \eta_{inv} = 97.09\%,\ \eta_{mp} = 27.41\% \text{ and } \eta_{sys} = 1.87\% .$$

The measured absolute maximum of these efficiencies are:

$$\eta_{mp} = 34.12\% ,\ \eta_{sys} = 2.4\% ,$$

$$\eta_{pv} = 7.65\%, \text{ and } \eta_{inv} = 99.36\%,$$

(e) The increase of ambient temperature results in increasing the PV cell temperature to exceed the standard value amounting to 25°C, which results in decreasing the output power of the PV module (-0.52%/1°Ċ) and consequently in reducing the daily output of the pumping system. The performance of system1 during a clear hot summer day (July 18) where E_{sd}=4.893 kWh/m^2.day and V=70.92 m^3/day are illustrated in Fig. 3.

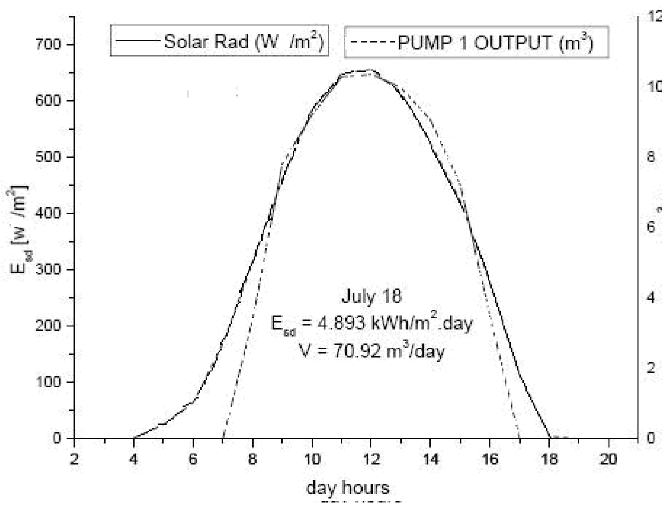

Fig. 3 The water discharge of system 1 and the solar radiation intensity in function of the day hours during a hot summer day

The dropping of V is referred to as the height of ambient temperature on this day, since on a cold day (March 27) of the same E_{sd}, the system delivers V=81.8 m^3/day. Table 2 has been established from large number of daily measurements to demonstrate the negative effect of increasing the ambient temperature on the system output at nearly constant solar radiation intensity.

TABLE 2 THE HYDRAULIC OUTPUT OF THE SYSTEM IN FUNCTION OF TEMPERATURE AT ALMOST CONSTANT DAILY SOLAR RADIATION INTENSITY

Date	Solar radiation W/m^2	Pump 1 l m^3/day	Pump 2 m^3/day	Daily average temperature.°C
Feb 28	5.365	98.62	91.05	13.2
May 31	5.368	81.90	80.66	24.3
August 4	5.367	76.46	74.57	32.7
September23	5.364	72.55	70.88	35.2

B. Results of the Controlled PV Pumping System

The PVPS in Fig. 1 with the control system, identified logically by its truth table in Table 1, had been continuously tested for two years. The obtained testing results were compared with the testing results of the uncontrolled system. The main results are summarized as follows:

(a) The controlled system starts pumping earlier in the morning when *G* exceeds 100 W/m^2 and stops later in the evening when *G* falls below 60 W/m^2, which means extending the daily operation time as indicated in Fig. 4. The actual connections are identified in Table 1. Based on measurements on a day where E_{sd}=2.815 kWh/m^2.day, the system delivers 105.33 m^3/day which exceeds the output of the uncontrolled system at similar solar radiation by 14.5 m^3/day.

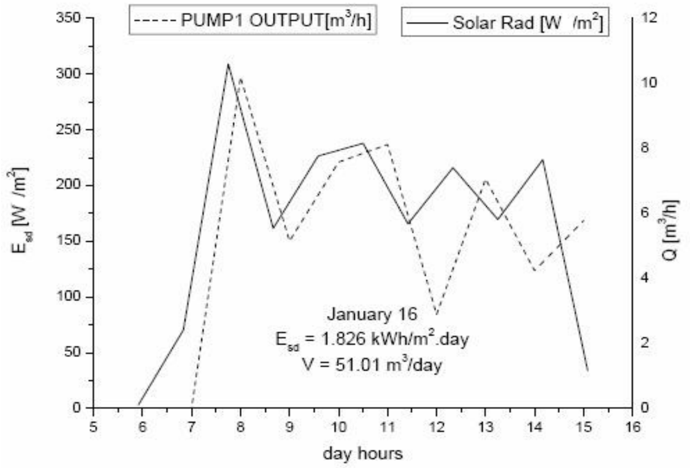

Fig. 4 The water discharge of system 1 and the solar radiation intensity in function of the day hours during a winter day

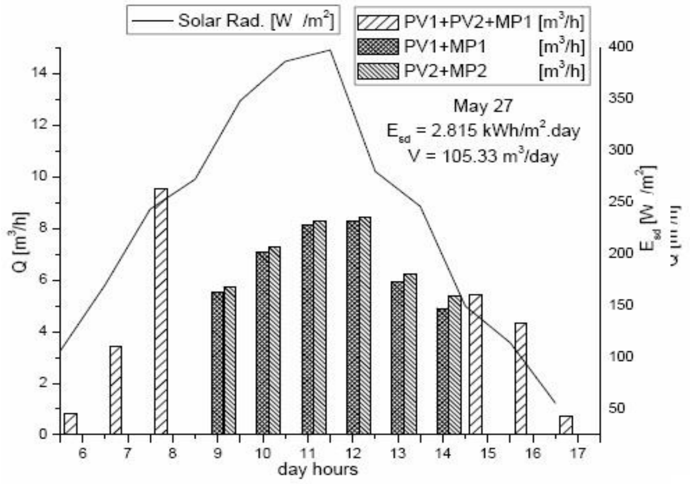

Fig. 5 The water discharging of the controlled pumping system and the solar radiation intensity in function of day hours on a winter day of low solar radiation

(b) In winter days when the total daily solar energy is very low, the control system switches both PV arrays all the day in parallel to drive only one motor pump. Fig. 5 illustrates such a scenario for E_{sd}=1.826 kWh/m^2.day, where the system delivers 51m^3/day which is about 4.25 m^3 higher than the daily output of the uncontrolled system at similar E_{sd}.

(c) The control system is useful especially in winter, where the solar radiation intensity varies randomly and the total daily solar energy is below 3 kWh/m^2.day. On such days a maximum increment of daily water pumped amounting to 16% was measured (Fig. 4).

(d) In summer months or cloudless periods, the control system works only for short periods in the morning and in the evening, while each pump will be supplied through one inverter from one PV array. In this case, the difference between the daily output of uncontrolled and controlled system is very small.

(e) Consequently, on annual basis, the controlled PVPS had delivered 7.4% more water than the uncontrolled system.

C. Conclusions

Based on four years testing of this PVPS, beside testing of numerous other systems on other desert wells [1, 7], the following conclusions can be made:

(a) Utilization of PV generators for water pumping became an effective and reliable method for water supply especially in rural areas lacking of electricity. With respect to daily water demands, pumping heads and cost of diesel fuel, PV systems compete economically within a large range with diesel-powered system in any area of high solar energy potential [1, 8].

(b) The peak efficiency of the used PV module is relatively low (η_{pv}=8% at STC) and thereby the overall maximum efficiency is low (η_{sys}=2.24%). Higher η_{sys} could be achieved in other PVPS where we had PV modules of higher efficiencies (η_{pv}=12%) and motor pumps of better matching with the pumping heads [7, 8]. In such system η_{sys} had achieved 4%.

(c) The increase of ambient temperature decreases considerably the output of the PV pumping system (Fig.3, Table 2). Therefore, this issue should be seriously considered when estimating the safety factor in the design.

(d) Utilizing of control system enables, during periods of low solar radiation, better exploitation of the produced PV power and driving the motor pump closer to its rated power, which increases the daily average of pumped water. As mentioned an increase of 7.4% was achieved, and higher percentage could be achieved if the rated power of the two motor pumps was not equal but for instance with a ratio of about 1:2.

(e) The control system allows operating the two motor pumps alternately which elongate their lifetime (Table 1). The cost of the control system, compared with the cost of the PVPS components, is relatively low and is justified by its extra advantages.

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