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Experimental study of a direct-coupled PV water pumping system

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Abstract: A solar photovoltaic (PV) water pumping system consists of a pump powered by solar electricity, which elevate groundwater in a storage tank, aiming to irrigate the crops. Certainly, the direct-coupled PV water pumping system is the most reliable low-cost configuration. This study is focus on a such direct-coupled system operating in the specific climate of the Banat Plain. The experimental setup, located in Timisoara, was monitored from April 25 to September 30, 2013, thus covering the entire irrigation period. The system performance and the distribution in time of water pumped are assessed in connection to the solar radiative regime.

Keywords: solar photovoltaic (PV) water pumping, irrigations, Banat Plain

1. INTRODUCTION

In order to meet the energy demand and to reduce the environmental impact, the idea of integrating renewable energy sources, such as photovoltaic (PV), with water pumps has been proposed by many researchers. A comprehensive review on using renewable energy sources for power supply of water pumping systems is presented in [1].

In this paper we study the direct-coupled PV water pumping system. The direct coupling of the PV array to the load is definitely the lowest-cost PV system. Generally, the system consists of a PV module directly connected to a DC motor driving a centrifugal pump. Due to its simplicity (it not includes batteries and controllers) such a system is fully reliable. The system basically *stores* potential gravitational energy instead of storing electricity.

The direct-coupled PV water pumped systems were intensively investigated in the last decades. Ref. [2] reviewed the existing studies on the subject published before the middle of ’95. A dynamic model of a complex system including PV module, battery as power buffer between PV array and load, electrical motor and water pump is presented in Ref. [3]. A model for optimal sizing the different components of a PV pumping system using water tank storage was proposed recently in [4]. The model operates with various scenarios based on the water consumption profiles, total head, tank capacity and PV array peak power.

In this paper we present an experimental study on a direct-coupled PV water pumping system. The experimental setup was built on the Solar Platform of the West University of Timisoara and it is briefly described in Sec. 2. The pump was monitored five months during the spring and summer seasons, period in which the crops are irrigated in the Banat plain. The system is assessed from two different perspectives: (1) the volume of water pumped and its distribution in time and (2) the influence of the solar radiative regime on the system performance. The first issue is essential when a on a direct-coupled PV water pumping system is sized for operating in the Banat plain. The second issue is an attempt to take a broad view on the case study, aiming to generalize the results. Two simple measures related to the state of the sky, sunshine number and sunshine stability number, are used to quantify the solar radiative regime. Both measures are introduced in Sec. 3. Section 4 is devoted to the presentation and understanding the experimental results.

2. EXPERIMENTAL SETUP

The experiment was conducted on the Solar Platform of the West University of Timisoara (http://solar.physics.uvt.ro/). The Solar Platform includes a radiometric station (SRMS) and three experimental setups for testing PV systems. SRMS is equipped with DeltaOHM first class pyranometers in accordance with ISO 9060 standard [5]. Global, diffuse, reflected and total solar irradiances are monitored. All the sensors are integrated into a NI PXI acquisition data system. Measurements of all parameters (electrical, meteorological, radiometric) are simultaneously performed at equal time intervals of 15 seconds, 24/7.

Schematic of the experimental setup used for testing the direct coupled PV pumping system is presented in Fig. 1. Two photos of the main components, the PV module and the water pump, are presented in Fig. 2. The experimental setup consists of a PV pump SHURflo 2088-403-144 powered by a PV module FVG90M. The main characteristics of the PV pump and the PV module are presented in Table 1 and Table 2, respectively.

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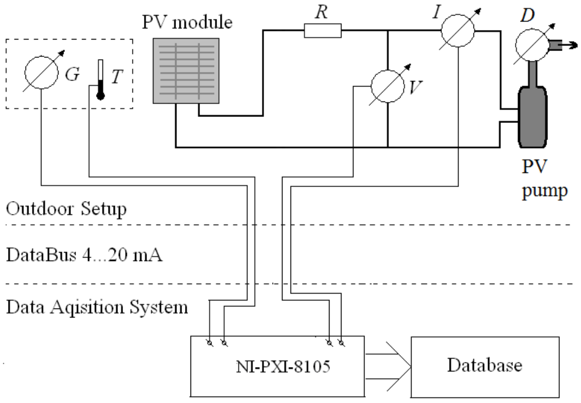
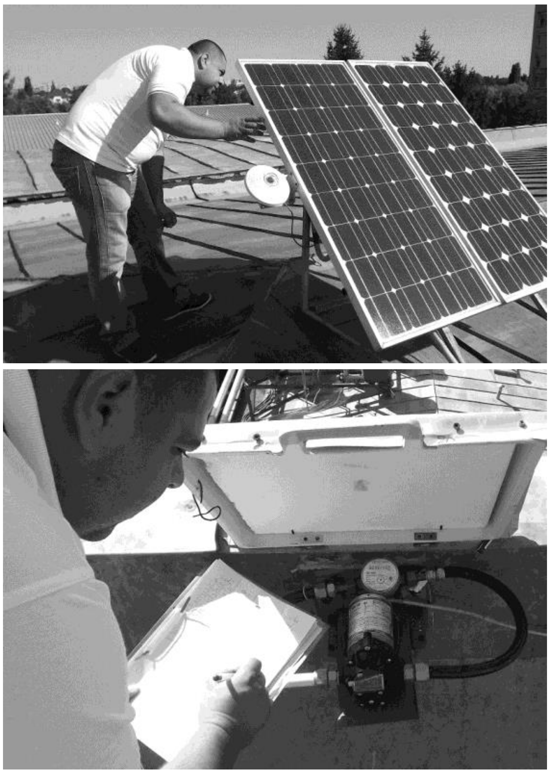


Figure 1. Schematic of the experimental setup. *G* is a pyranometer measuring solar irradiance on the PV module surface. *T* is a ventilated and shadowed thermal sensor measuring the environmental temperature. *D* is a standard flowmeter**.**

Table 1. The main characteristics of the SHURflo 2088-403-144 PV pump

Type	Positive displacement 3 chamber diaphragm pump
Operation	One way operation, check valve
Voltage	12V DC nominal
Pressure switch	3.1 bar Shout-Off, Turn On 1.7±0.35 bar
Motor	Permanent magnet
Performance	Open/10.6/3.1
(pressure [bar]/debit [l/min]/current [A])	0.7/7.8/3.7
	1.4/6.2/4.2
	2.1/4.7/4.5
	3.5/2.2/4.5



a.

b.

Figure 2. Photos of the experimental setup for studying a direct-coupled PV water pumping system: (a) PV module FVG90M (on the right side) and LPPYRA 02 pyranometer measuring solar irradiance on the module surface; (b) SHURflo 2088-403-144 water pump.

Table 2. The main characteristics of the FVG 90M PV module

Nominal power	90W
Open circuit voltage	22.3 V
Short circuit current	5.37 A
Voltage at MPP	18.5 V
Current at MPP	4.86 A
Thermal coefficient of the open circuit voltage	- 0.0034 °C^{-1}
Thermal coefficient of the short circuit current	0.0005 °C^{-1}
NOCT	45 ± 2 °C
Module surface	0.596 m^2

The pyranometer *G* in Figure 1 measures the solar irradiance on the PV module surface. *T* is a thermal sensor which measures the environmental temperature. The resistor *R* limits the current, serving to protect the load when the sun is shining strongly. Water is pumped from one thank into another thank located at an elevation of 4.5 meters from the first. From the second thank the water flows to the first under the action of gravity. Thus, the water flows in a closed loop. The volume of water pumped is measured by the flowmeter *D*.

3. CHARACTERIZATION OF THE SOLAR RADIATIVE REGIME

In order to assess the solar radiative regime, two measures related to the state of the sky are used in this paper: sunshine number (SSN) and sunshine stability number (SSSN).

SSN quantify the relative position of the sun and the clouds. It is defined as a time dependent binary random variable [6]:

$$SSN_t = \begin{cases} 0 & \text{if the sun is covered at time } t \\ 1 & \text{otherwise} \end{cases} \quad (1)$$

Series of SSN values can be derived from the series of measured solar irradiance values by using the World Meteorological Organization sunshine criterion [7]: the *sun is shining* at time moment *t* if direct solar irradiance exceeds 120 W/m^2:

$$SSN_t = \begin{cases} 1 & \text{if } \ (G_t - G_{d,t}) / \sin h_t > 120 \text{ W/m}^2 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where G_t and $G_{d,t}$ denote the global and diffuse solar irradiance at the moment *t*, respectively. The average value of SSN over a time interval Δt equals the relative sunshine σ in Δt. Its definition is $\sigma = S / S_0$, where $S_0 \equiv \Delta t$ and S is the bright sunshine duration in Δt. A low S / S_0 value is an indirect indication of a high cloud cover amount.

In order to quantify the stability of the solar radiative regime, SSSN, a parameter related to SSN, was defined in Ref. [8]:

$$SSSN_t \equiv \begin{cases} 1 \text{ IF } \mathrm{SSN}_t < \mathrm{SSN}_{t-1} \text{ (IF } \mathrm{SSN}_1 = 1) \\ \text{OR } \mathrm{SSN}_t > \mathrm{SSN}_{t-1} \text{ (IF } \mathrm{SSN}_1) = 0 \\ 0 \text{ OTHERWISE} \end{cases} \quad (3)$$

The average value of SSSN over Δt ($\overline{\mathrm{SSSN}}$) ranges between 0 and 1/2. The solar radiative regime is *fully stable* in the first case and *fully unstable* in the last case.

Different elementary statistical and sequential properties of SSN were reported [6, 8-9].

4. RESULTS AND DISSCUSSION

The experimental setup was monitored five months, from April 25, 2013 to September 30, 2013. This time period covers the entire irrigation period in the western part of Romania. The meteorological and the radiometric quantities were recorded automatically, while the flowmeter was read in the morning before to start the pump. Here we discuss the system behaviour from two perspectives: the volume of water pumped and the dependence of this quantity on the solar radiative regime.

Figure 3 shows the cumulative volume of water pumped during the test period as function of Julian day. It can be seen that the cumulative volume varies almost linearly with the Julian day. This variation can be approximated by the following linear equation:

$$V = 2.2 \cdot j - 235 \quad (4)$$

where V is the pumped volume, j > 120 is the Julian day. During the test period the total volume of water pumped was 369.2 m^3, which represents a daily average of 2.33 m^3/day. Table 3 shows the volume of water pumped month by month and its daily mean value. The maximum volume of 91.3 m^3 was reached in July, representing a daily average of 2.94 m^3. This is due to the fact that in July many days were completely sunny (σ_m = 0.762). The highest value of daily mean of solar irradiance H_m = 458.2 W/m^2 was also reached in July. In May and June the volume of water pumped was approximately 2/3 to that of July.

The volume of water pumped cannot be related directly to relative sunshine. Since the monthly solar irradiance depends strongly on season, even if every day of January would be sunny, the volume of water pumped will be less than in July. Table 3 shows that the monthly volume of water pumped depend in a complex manner on the monthly mean of solar irradiance, relative sunshine and daylight hours.

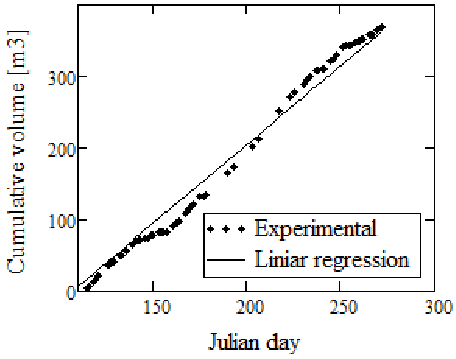


Figure 3. Cumulative volume of water pumped during the test period

Table 3. Different monthly values of the measured quantities: volume of water pumped (V); average of the daily volume of water pumped (V_m); average of daily relative sunshine; average of daily total solar irradiation (H_m).

Month	May	Jun	Jul	Aug	Sept
V [m^3]	58.5	60.4	91.3	88.4	48.4
V_m [m^3/day]	1.88	1.94	2.94	2.85	1.61
Daylight [hours]	14.9	15.6	15.3	14.1	12.5
σ_m	0.494	0.504	0.762	0.704*	0.465
H_m [W/m^2]	382.5	351.7	458.2	440.1*	364.3

*SRMS did not work during 18 to 26 August -maintenance

Next we will focus on the daily variation of the volume of water pumped. In an experiment conducted in April 25, 2013 we determined a threshold value of total solar irradiance on the PV module surface H_S = 450 W/m^2 at which the pumped starts/stops. It means that when total solar irradiance is less than 450 W/m^2 the pump does not operate, it starts at 450W/m^2 and the water flow increases with increasing the solar irradiance.

The performance of direct-coupled PV water pumping system depends on the relative position of the Sun and the clouds. As it is defined in Eq. (3), SSN is an appropriate parameter for describing the relation between the pump performance and the state of the sky. The dependence of the volume of water pumped on the daily solar radiative regime is assessed in Fig. 4. These graphs display the total solar irradiance measured on the surface of the PV module in two different time periods of June. The first period from 10 to 13 June was mainly characterized by an unstable solar radiative regime, while the second period from 19 to 20 June was characterized by stability. Daily mean values of SSN and SSSN along with the volume of water pumped are indicated on each graph. In every day around the summer solstice, the apparent trajectory of the Sun is approximately the same. We can assume that during this period the variation of solar irradiance under clear sky does not change substantially from one day to another. Thus, these graphs isolate the dependence of the volume of water pumped in each day on the state of the sky.

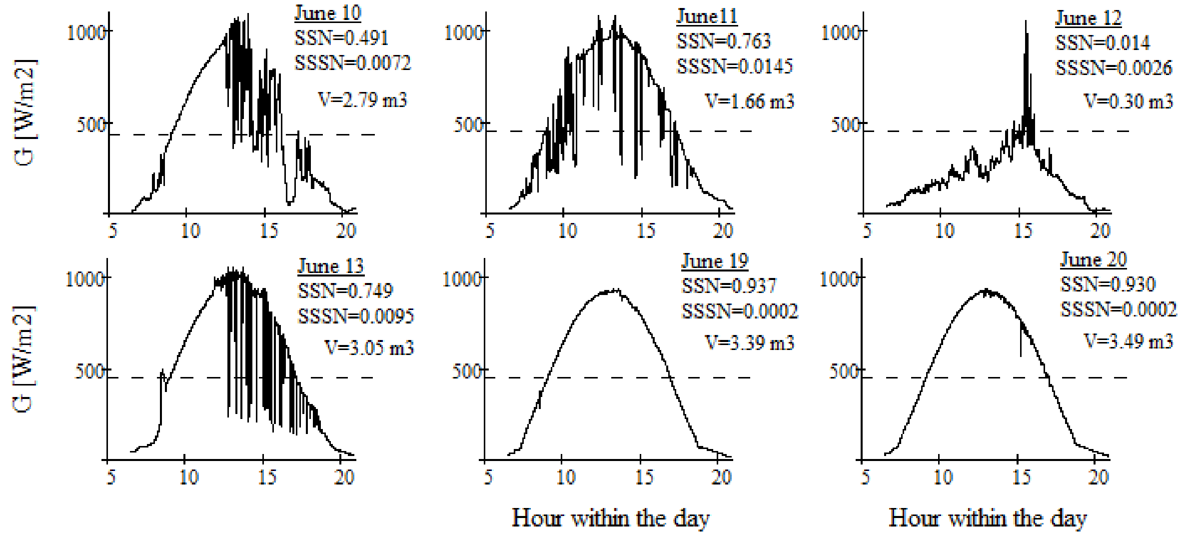


Figure 4. Total solar irradiance measured on the surface of the PV module as function of time in six days of June 2013. Daily mean of sunshine number (SSN), daily mean of sunshine stability number (SSSN) and the volume of water pumped are displayed on the graphs. The dashed line indicates the threshold value

The minimum volume of water V = 0.30 m^3 was pumped in June 12, a cloudy day ($\overline{SSN} = 0.014$) with a small period in which the sun shone. The maximum volume of water V = 3.49 m^3 was pumped in June 20, an almost perfectly clear sky day ($\overline{SSN} = 0.930$). The days June 11 and June 13 where characterized by the same cloud cover amount ($\overline{SSN} = 0.763$ and $\overline{SSN} = 0.749$). However, the volumes of water pumped in these days were very different: V = 1.66 m^3 in June 11 and V = 3.05 m^3 in June 13. As the corresponding graphs from Fig. 4 shows, the stability of the solar radiative regime made the difference. June 11 was characterized by a high instability ($\overline{SSSN} = 0.0145$) while June 13 was characterized by a moderate instability $\overline{SSSN} = 0.0095$. In June 10, a day with $\overline{SSN}$ lesser than that in June 11 but more stable, the volume of water pumped was significantly higher than that in June 11.

4. CONCLUSIONS

In this paper we presented the results of a case study on a direct-coupled PV water pumped system. The system consisted on a 90W PV module which supplied a small water pump. During a period of five months, the system pumped a remarkable volume of water of 369.2 m^3 at an elevation of 4.5 m. Taking into account the market price for components, the system cost is less than 180 euro.

The volume of water pumped daily depends clearly on the total solar irradiance on the module surface. Assuming clear sky days, the volume of water pumped can be easy estimated knowing only the output power of the PV module (a simple model is presented in [10]). However, the days are not all sunny. The analysis shows that together the sunshine number and the sunshine stability number are appropriate parameters for modelling the volume of water pumped in real meteorological conditions.

The case study presented here illustrates the performance and the costs of a direct-coupled PV water coupled system. The results can be easy extrapolated to larger systems operating in the Banat plain. Our further effort will be devoted to accurately relate the volume of water pumped to the local meteorology.

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