A SOFTWARE TOOL TO COMPUTE AUTONOMOUS PHOTOVOLTAIC WATER PUMPING SYSTEMS

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Abstract: The applications of photovoltaic systems (PVS) have been increased rapidly in the last years. The water pumping systems are included in between the photovoltaic applications. This paper describes the features of a software tool, which computes an autonomous PV water pumping system. First, this tool calculates the power needed for pumping water considering effects of crop and climatologically parameters, the size of the area to be irrigated, pipeline friction losses and so on. Consequently, this tool enables the user to estimate the monthly or daily output power of PV array, the number of PV panels needed and the required PV array size, the total capacity and the number of batteries, the number of days of autonomy and finally the volume of water tank. The development software tool can be utilized in designing the real water pumping systems as well as in research and educational processes.
Keywords: Photovoltaic system, software tool, water pumping.

1 Introduction

Photovoltaic (PV) power system can convert sunlight directly into electricity. The basic building block of PV system is the solar cell. There are different materials suitable for making PV cells, like crystalline silicon, poly-crystalline silicon, amorphous silicon, cadmium telluride, etc. For a typical solar cell the most common structure is a semiconductor material into which a p-n junction, has been formed. The electric current flows in one direction, and thus the electricity generated is termed direct current (DC). In case that the DC current cannot be used directly, other system components will be needed. These may include battery charge controllers, batteries, inverters, and wiring with appropriate safety devices. Today’s commercial PV systems can convert from 7% to 17% of sunlight into electricity. Users of PV power systems appreciate their quiet, low maintenance, pollution-free, safe and reliable operation. Last years, their cost has dropped and PV modules now cost around 5 Euro per Watt (Gustafson and Morgan, 2004).

The three typical configurations of PV power systems are: autonomy, hybrid and grid-connection. Autonomous power systems are not connected to the main utility grid and are used in remote areas. They may incorporate batteries, which store energy from the PV modules during the day, for use at night or in periods of low solar radiation. Alternatively, they may provide the application entirely, with no need for batteries. A hybrid system is a good option for larger systems that need a steady power supply, when there is not enough sunshine at certain period of the year. Usually, a hybrid system consists of PV modules and a fuel-fired generator. A grid-connected system generates its own electricity and feeds its excess power into the utility grid for later use (Natural Resources Canada, 2002).

In agricultural applications, where a small amount of energy in remote locations is needed, the autonomous PV power systems are a good solution. Today, several thousands hectares of remote cultivating land are not being used due to the high costs of pumping water by conventional methods. Therefore, solar pumping systems are widespread. They can be used to pump drinking water from wells or water for irrigation in agriculture. The demand for water is greater when the weather is hot and dry, precisely when the most solar energy is available. Simple non-storage types of PV power systems are ideal for many irrigation applications. However, the difficulty is predicting the performance of a direct-coupled PV pumping system. The relationship between pumping rate and the radiation is a non-linear. At high radiation levels, the rate of increase of the pumping rate with increasing radiation is smaller than at intermediate radiation levels. Both the existence of a radiation threshold and the non-linear dependence of flow on radiation level complicate the prediction of direct-coupled PV pumping system performance (Kou et al., 1998). In this case, water is pumped when the sun shines and is stored directly in a tank that is installed at a higher level for later use by gravity feed. It makes PV powered irrigation systems economically attractive. Normally, the excess energy generated in autonomous PV systems during sunny periods is stored in batteries. The batteries then provide electricity at night or when there is not enough solar radiation. For these applications, the number of watts in the array and the capacity of the batteries is carefully sized to give optimum performance (Poulek and Libra, 2006).

This paper describes a user-friendly software tool to compute autonomous photovoltaic water pumping systems and presents some examples to demonstrate how it can be applied.

2 Materials and Methods

Theory

A computer program has been developed to simulate the irrigation performance of the PV systems under different climate conditions. The program is based on mathematical models in order to properly size the system components: the PV array and pumping subsystem.

Step 1-Determination of water pumping power: According to Royer et al. (1998) the daily hydraulic energy demand E_h [J/day] corresponding to lifting water to a height h_o [m] with a daily volume Q [m^3/day] is:

$$E_h = \rho \times g \times Q \times h_o \qquad (1)$$

Where g is the acceleration of gravity (9,81 m/s^2), ρ the density of water (1000 kg/m^3). This hydraulic energy converts into an electrical energy requirement:

$$P = \frac{E_h}{PT \times PTF \times \eta_a} \qquad (2)$$

Where P [kW] is the power needed for pumping water, PT [h/day] is the pumping time, PTF is the pumping time factor and η_a is the pump system efficiency.

Step 2-Tilt angle selection of PV array: PV collectors can be fixed, adjustable or tracing. Adjustable collector allows the tilt angle to be varied manually throughout the year to maximize output year round. The tilt angle β of each PV collector is determined by formulas β=φ±15º or β=φ, where φ is the geographic latitude. In practice, it has been found that the tilt angle β=φ-15º is better for summer months.

Step 3-Determination of the average daily solar radiation falling on the PV array for each month: In base of tilt angle of PV array calculated the average daily value of solar radiation energy gain G_t [kWh/m^2/day]:

$$G_t = \frac{k_c \times I_{hs} \times 10^3}{d \times 3600} \qquad (3)$$

Where I_{hs} [MJ/m^2] is the average monthly radiation on horizontal surface, k_c is conversion factor and d [days] is days per month.

Step 4-Determination of day autonomy: If the daily radiation or the minimum peak sun hours (PSH) over the period of operation of the load is known for a location, the numbers of days of autonomy can be estimated by the following equations (Messenger and Ventre, 2004):

$$D_{crit} = -1{,}9 \times PSH_{min} + 18{,}3 \qquad (4)$$

$$D_{non\text{-}crit} = -0{,}48 \times PSH_{min} + 4{,}58 \qquad (5)$$

Where D represents the number of storage days required, either for critical or non-critical storage.

Step 5-Selection of PV module characteristics: The next step is to select an appropriate module that gives a maximum power point voltage as close as possible to the voltage at which the subsystem attains maximum operating efficiency. In case that the DC current cannot be used directly, it is necessary to choose other balance of the system components.

Step 6-Determination of electrical power losses: When designing a PV system it is necessary to determine the electrical power losses in the other system components (wiring, MPPT, inverter, etc.). For example wire cross-sections should be selected to limit resistive losses to less than 5%.

Step 7-Determination of peak PV output: The determination of the peak PV output P_{PV} [kW/day] is easily performed according to the following equation (Wenham et al., 2007):

$$P_{PV} = \frac{E'_h}{\left(PSH\right)_{min}} \tag{6}$$

Where E_h' [kWh/day] shows the increase in E_h due to the losses of PVS and $(PSH)_{min}$ is the minimum value of peak sun hours (equivalent number of hours per day when solar irradiance averages 1 kW/m^2).

Step 8-The effect of temperature on the maximum power output: The ambient air temperature, determines the operating temperature of a solar cell (Wenham et al., 2007). The specific parameters of PV module (I_{sc}, V_{oc}, P_m, FF) have been measured under standard test conditions. However, in practice they can be operated in different conditions. In nominal operating cell temperature (NOCT) (approximately 45 ºC), the temperature of PV modules (T_c) [ºC] will be different compared to the temperature of 25 ºC, in which the parameters have been initially measured.

$$T_c = T_a + \frac{\left(NOCT - 20\right)}{0{,}8} \times I_t \tag{7}$$

Where T_a [ºC] is the mean daily ambient air temperature, I_t [kW/m^2] is the solar radiation on PVS surface and NOCT [ºC] is the nominal operating cell temperature. The temperature dependency of V_{oc} is approximated by the following equation:

$$V_{oc} = V_{oc(initial)} - n_s \times 0{,}0023 \times (T_c - 25) \tag{8}$$

Where n_s is the number of solar cell that are encapsulated in the PV module. The effect of temperature on the maximum power output P_m [W] is as follows:

$$P_m = I_{sc} \times V_{oc} \times FF \tag{9}$$

Where I_{sc} [A] is the short circuit current, V_{oc} [V] is the open circuit voltage and FF is the fill factor.

Step 9-Photovoltaic system sizing: The total number of modules is the product of the number in parallel and the number in series. The number of modules in parallel is determined by dividing the derated array current by the rated module current. The number of modules in series is determined by dividing the nominal system voltage by the lowest anticipated module voltage of a module supplying power to the system (Messenger and Ventre, 2004).

Step 10-Determination of area of the PV station: The PV panels should be mounted facing due south in a location where they receive maximum sunlight throughout the year. The area of PV station S_{PV} [m^2] is given by:

$$S_{PV} = \frac{c}{b \times cos\beta} \times S_{CS} \tag{10}$$

Where c [m] is the distance between rows of PV panels, b [m] is the width of PV panel, β [º] is the tilt angle and S_{CS} [m^2] is the cross section of the total area of the PV array.

Step 11-Battery selection: The energy generated by PV modules can be used immediately or stored in batteries for later use. The required battery capacity C_b [Ah] can be estimated:

$$C_b = \frac{Q \times d}{V_{DC}} \tag{11}$$

Where Q [Wh/day] is the total daily load, d [days] are days of storage and V_{DC} [V] is the voltage output of PV generator. The following expressions are used to determine the number of the batteries needed:

$$N_{bs} = V_{DC} / V_b \tag{12}$$

$$N_{bp} = C_b / C_n \times DOD \tag{13}$$

$$N_b = N_{bs} \times N_{bp} \tag{14}$$

Where N_{bs} is the number of batteries connected in series, N_{bp} is the number of batteries connected in parallel, V_b [V] is the battery voltage, C_n [Ah] is the nominal capacity and DOD is the depth of discharge. If more than four batteries are required in parallel, it is generally better to consider higher capacity batteries to reduce the umber of parallel batteries to provide for better balance of battery currents. For these applications the number of watts in the PV array E_{PV} [kWh] and the capacity of the batteries E_b [kWh] must be carefully sized to give optimum performance.

$$E_{PV} = P_{PV} \times PSH \times d \tag{15}$$

$$E_b = N_{bp} \times \left(N_{bs} \times V_b \times \left(C_n \times DOD \right) \right) \tag{16}$$

$$E_b > E_{PV} \tag{17}$$

It means that energy delivered by batteries will cover the energy demands of the water pumping system for long time (autonomy in days).

Step 12-Determination of the tank volume: When the sun shines the water is pumped and it is stored in a tank for later use. This is economically attractive for autonomous PV water pumping systems. The volume V [m^3] of the tank is defined by:

$$V = Q_t \times T \times d \tag{18}$$

Where Q_t [m^3/h] is the pumping system flow per hour, T [h] is the pumping time and d [days] is the autonomy in days of the system.

Software

This software tool allows the user to rapidly compute autonomous photovoltaic water pumping systems. It is a Microsoft Windows Multiple Document Interface application written in Microsoft Visual Basic. Multiple screens can be displayed simultaneously, allowing different sets of parameters to be selected and the results to be displayed. At the moment, it has been prepared only the Greek version. The English version will be prepared in the future.

3 Results and Discussion

The evaluated software is a unique tool developed by the Department of Agricultural Machinery & Irrigation team at Technological Educational Institute of Larissa (TEI/L) to assist in the design of autonomous PV water pumping systems. In this section, we show the results obtained by the above software tool. Each worksheet case includes inputs and results. Values that the evaluated software calculates based on the values of other input variables. When the results are consistent with the inputs, the results are complete. When the results are not consistent with the inputs, the results are pending.

Figure 1 presents an example worksheet of system crop and climatic parameters setting. Several additional worksheets are associated with this to set soil and irrigation parameters, pipelines friction losses (Fig. 2) and technical parameters of PV modules and batteries. This worksheet consists of a menu bar and parameters setting pane. In parameters setting pane the brown background indicates the calculated and pre-defined values and the green background indicates the new parameters setting. In the right upper side, it displays a basic help system that provides simple instructions. Action buttons in the menu bar determine what worksheet appears in the next active case. In the taskbar, click the Excel button to create an Excel file containing the data show in the data table. This feature allows the use of external spreadsheets. Both import values from spreadsheets and export values use the result of a spreadsheet calculation for the value of one variable that depends on the value of other variables.

Figure 3 presents the results summary table for an area in Larissa (Greece). It consists of menu pane, results and data pane, and results management tool bar. The color of actions buttons and text box backgrounds provides you, with information about the contents of the worksheet. The green background color of text boxes saws about the results and the violet background color provides you with the IS units.

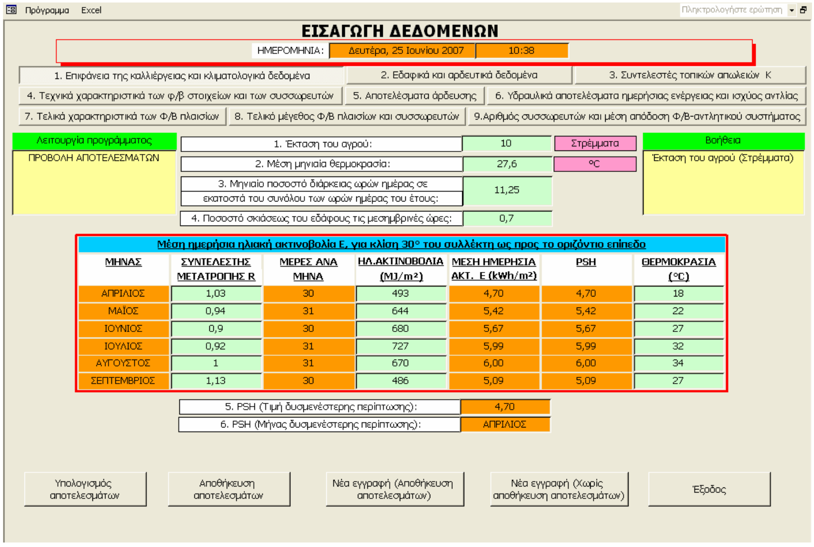

Figure 1 - System parameters setting

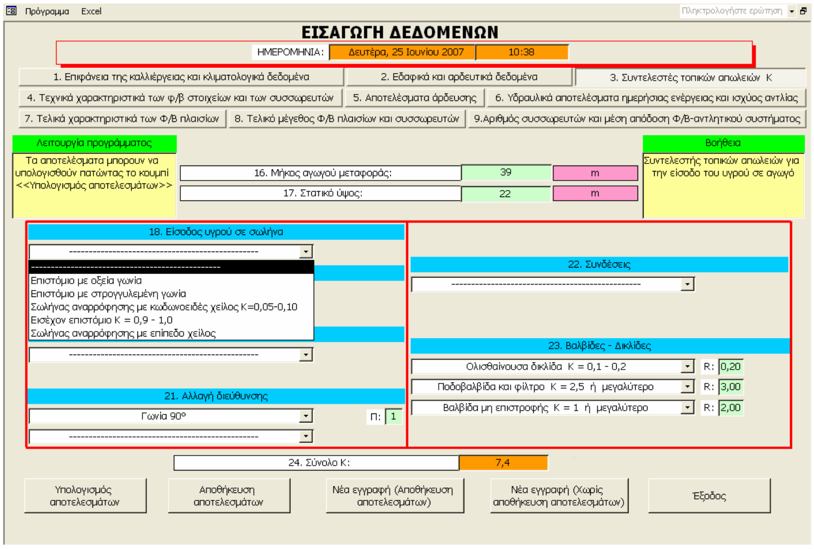

Figure 2 - Worksheet to set pipelines friction losses

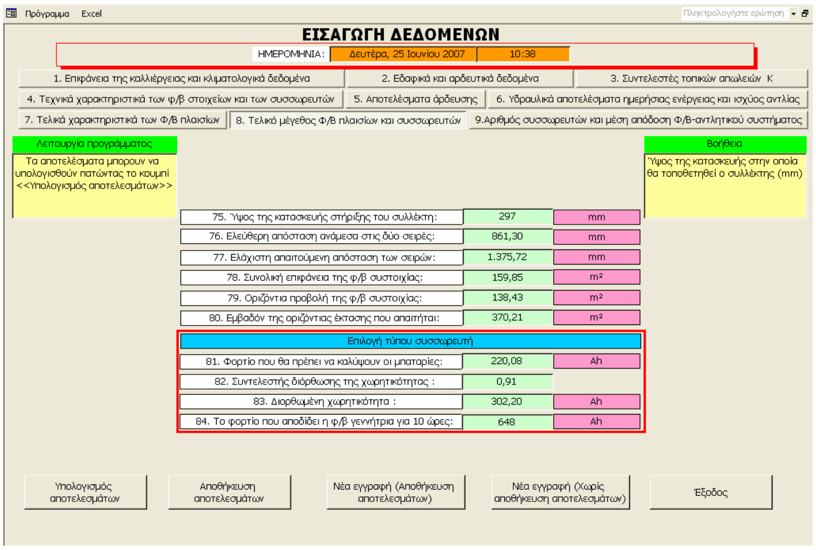

Figure 3 - Overview of the results summary for an area in Larissa (Greece)

By insertion different variables as areas to be irrigated, rootzone depths and total dynamic heads, verified the evaluated software tool (Fig. 4). In any case, the predicted total surface of PV array increasing according the variables growing. Also, the total surface of PV array is more affected by the growing of rootzone depth.

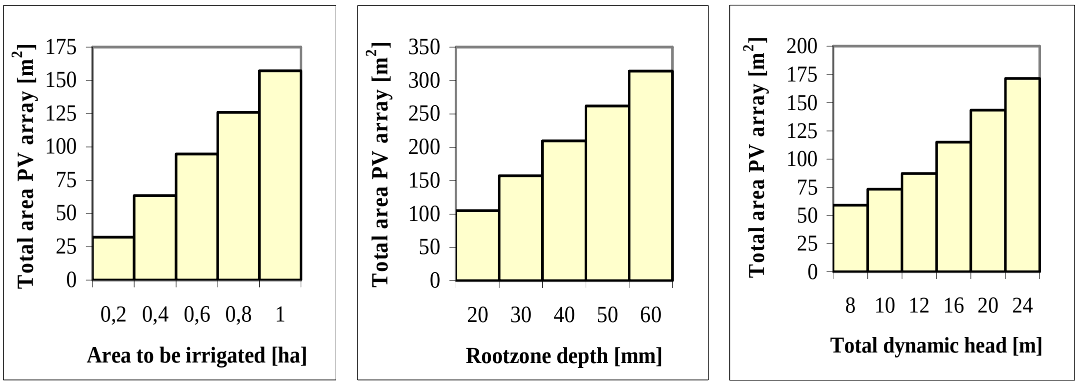

Figure 4. - The total surface of PV array predicted for different areas to be irrigated, rootzone depths ad total dynamic heads

4 Conclusions

The evaluated software is a user-friendly tool that provides computation of autonomous photovoltaic water pumping systems and how changing the PV generator characteristics, size of the area to be irrigated, rootzone depth or total dynamic head. Detailed analyses have shown that the software tool gives reasonable estimation of the total surface of PV array or the total number of modules. This means that the developed software tool can be used with confidence in designing the real water pumping systems as well as in research and educational processes.

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